



Gravitational waves from axions

Sep. 26th 2016 @Fermilab

**Joint KEK Theory
Fermilab Theory Meeting**

Fumi Takahashi
(Tohoku)

Higaki, Jeong, Kitajima, FT, 1512.05295, 1603.02090, Higaki, Jeong, Kitajima,
Sekiguchi, FT, 1606.05552, Takeshi Kobayashi, FT, 1607.04294

The Strong CP Problem

$$\mathcal{L}_\theta = \theta \frac{g_s^2}{32\pi^2} G^{a\mu\nu} \tilde{G}_{\mu\nu}^a$$

Experimental bound from neutron electric dipole moment reads

$$|\theta| < 10^{-10}$$

Why θ is so small is the strong CP problem.

cf. More precisely, the physical strong CP phase is

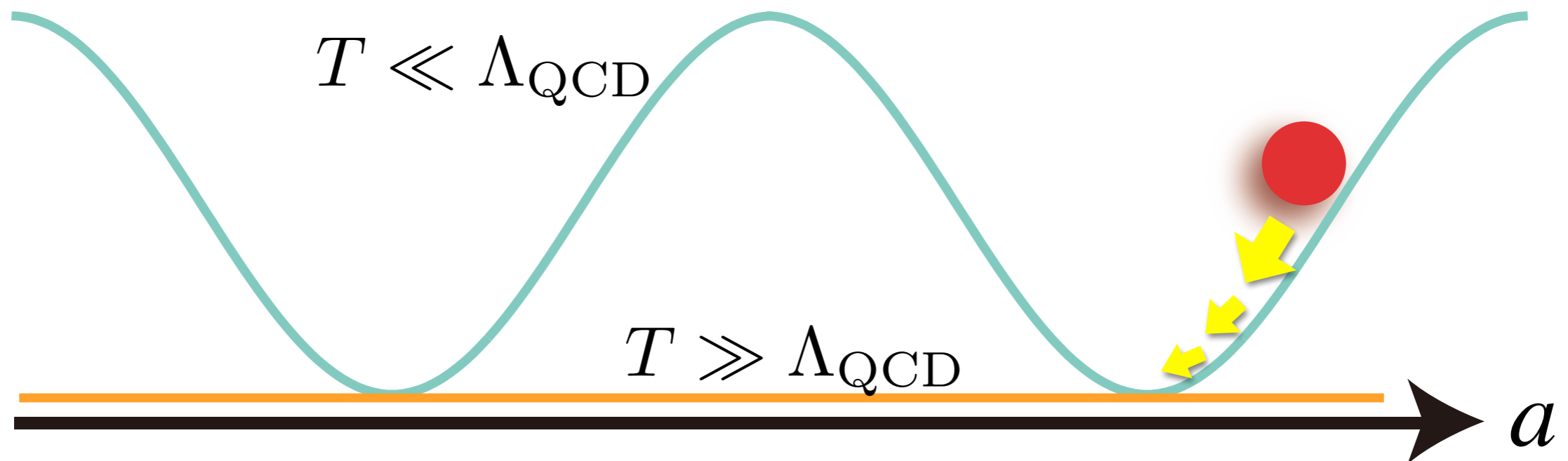
$$\bar{\theta} \equiv \theta - \arg \det (M_u M_d)$$

which makes the problem even more puzzling.

In the Peccei-Quinn solution, the strong CP phase is promoted to a dynamical variable:

Peccei, Quinn '77, Weinberg '78, Wilczek '78

$$\mathcal{L}_\theta = \left(\theta + \frac{a}{f_a} \right) \frac{g_s^2}{32\pi^2} G^{a\mu\nu} \tilde{G}_{\mu\nu}^a$$



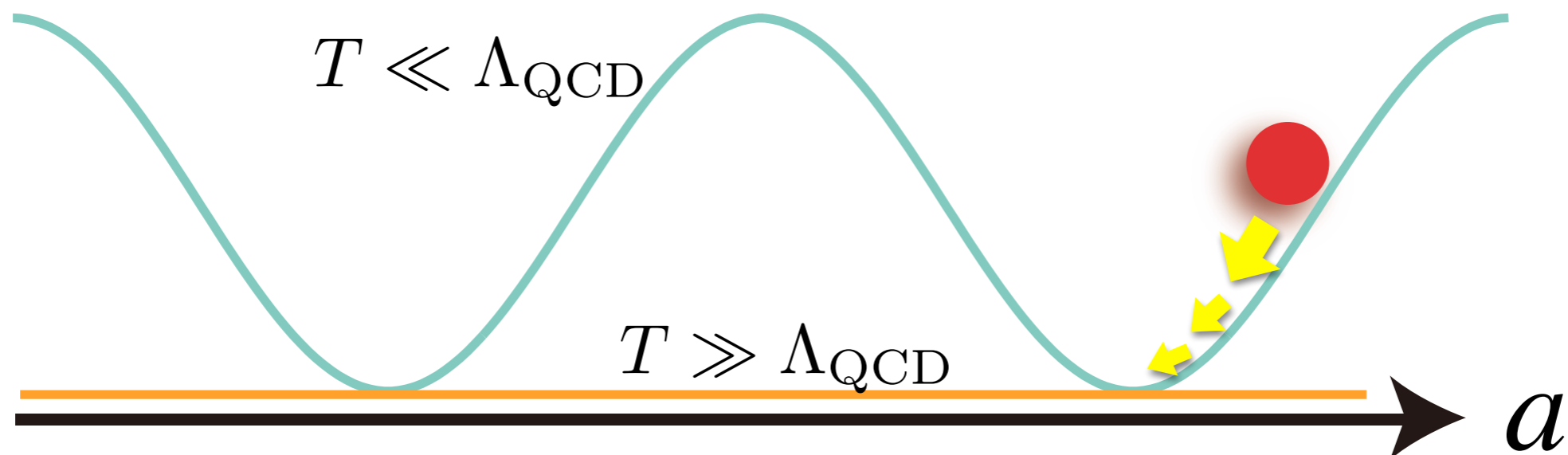
$$m_a \simeq 6 \times 10^{-6} \text{ eV} \left(\frac{f_a}{10^{12} \text{ GeV}} \right)^{-1}$$

Axion-like particles (ALPS) do not satisfy the above relation.

In the PQ mechanism, the axion DM is produced as coherent oscillations [misalignment mechanism].

$$\Omega_a h^2 = 0.18 \theta_i^2 \left(\frac{f_a}{10^{12} \text{ GeV}} \right)^{1.19} \left(\frac{\Lambda_{\text{QCD}}}{400 \text{ MeV}} \right) \text{CDM}$$

- + thermal production for small f_a **HDM**
- + non-thermal production from saxion decay **DR**





Production

Terrestrial

Celestial

Cosmological

Detection

Direct

LSTW,
Photon pol.
ALPS,OSQAR,
PVLAS,



Solar axion
CAST, IAXO



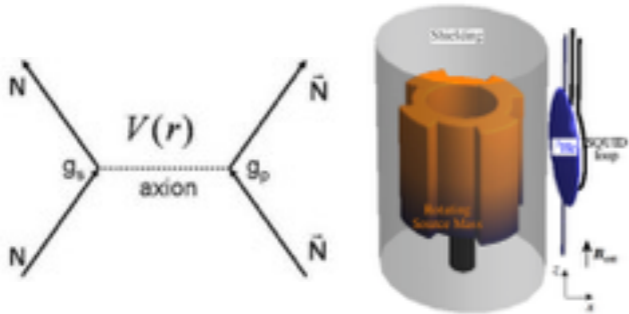
Axion DM

ADMX, CAPP,ORPHEUS
LC-circuits, CASPEr,
XMASS, EDELWISE,XENON100.

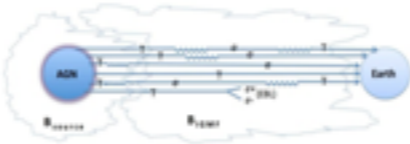


Indirect

Fifth force
ARIADNE

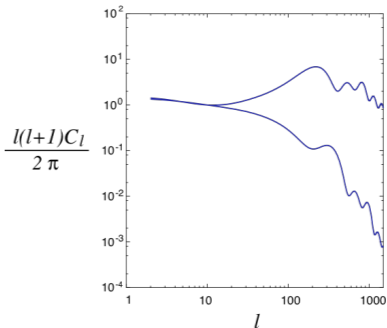


Excessive cooling
of WD, RGB, HB, NS
Spectral irreg.
Transparency
Fermi, IACT.



Isocurvature, DR,
spectral distortion,
caustics, GW, etc.

Planck, CORe+, PIXIE





Production

Terrestrial

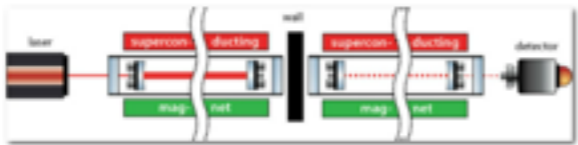
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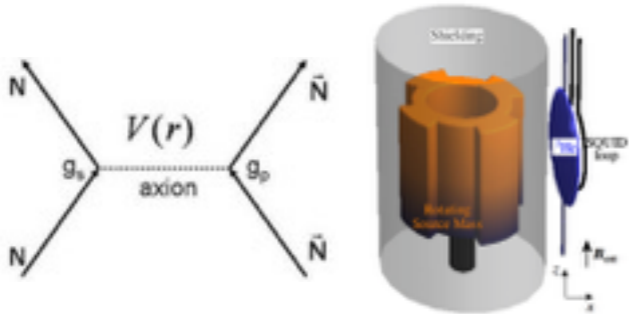
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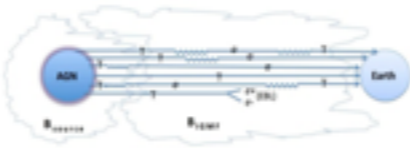
Tension with
high-scale inflation?

Indirect

Fifth force
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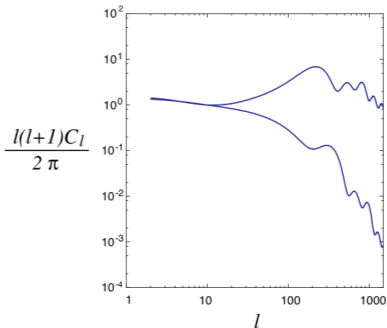


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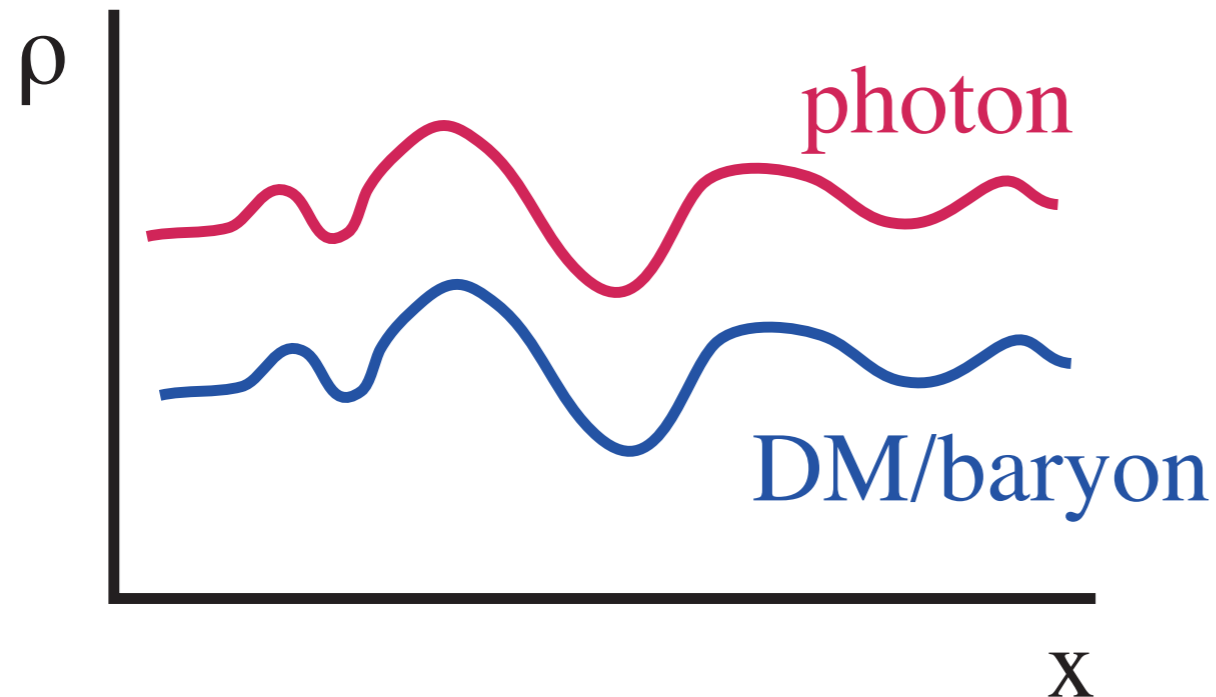
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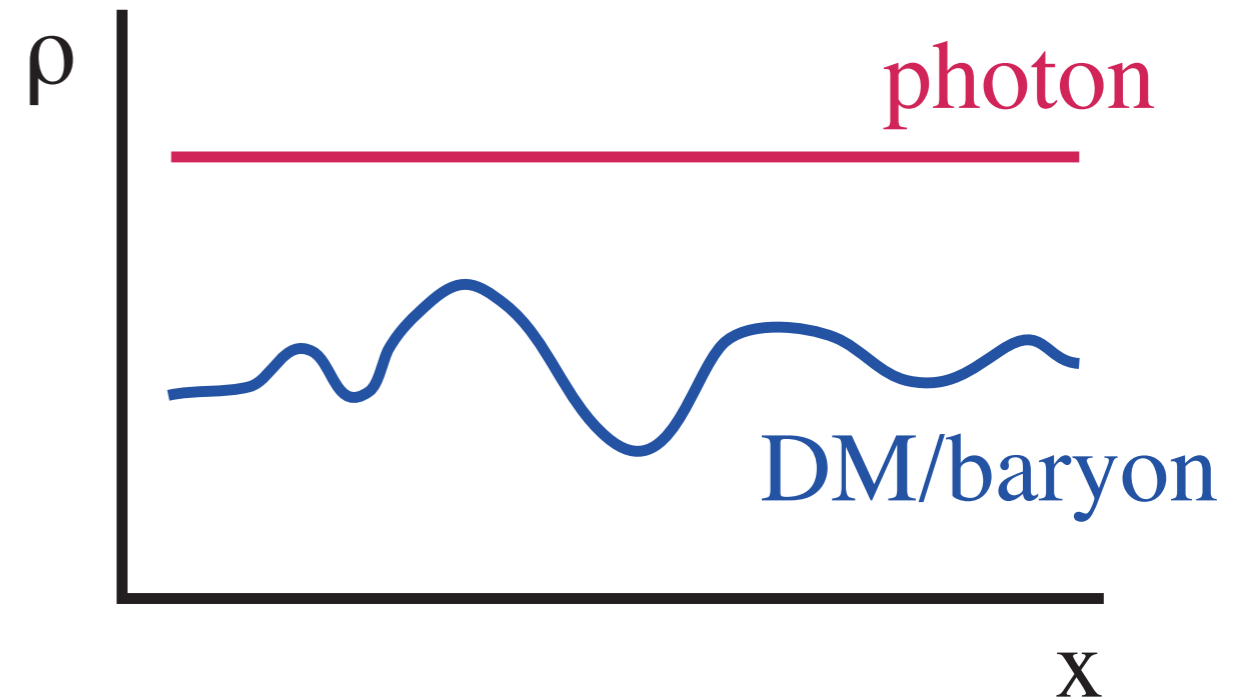


Axion isocurvature perturbations

Adiabatic perturbation



Isocurvature perturbation

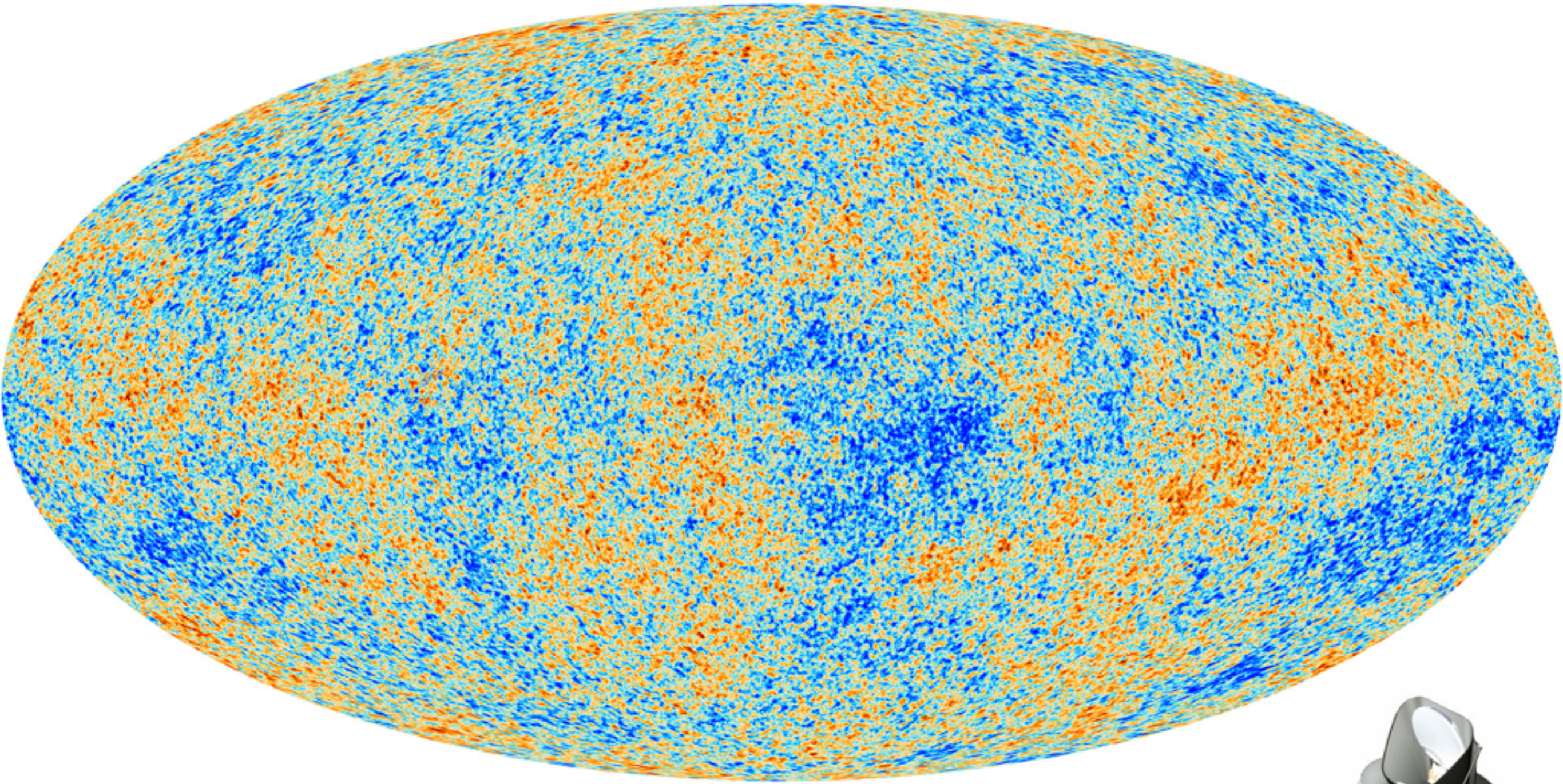


$$S = \frac{\Omega_a}{\Omega_{\text{CDM}}} \frac{\delta\Omega_a}{\Omega_a} = \frac{\Omega_a}{\Omega_{\text{CDM}}} \frac{2\delta\theta_i}{\theta_i} = \frac{\Omega_a}{\Omega_{\text{CDM}}} \frac{H_{\text{inf}}}{\pi\theta_i f_a}$$

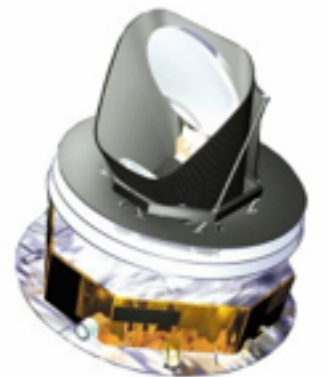
$$\beta_{\text{iso}} = \frac{\mathcal{P}_S}{\mathcal{P}_{\mathcal{R}} + \mathcal{P}_S} < 0.038 \quad (95\% \text{ CL})$$

Planck 2015
(Planck TT, TE, EE + lowP)

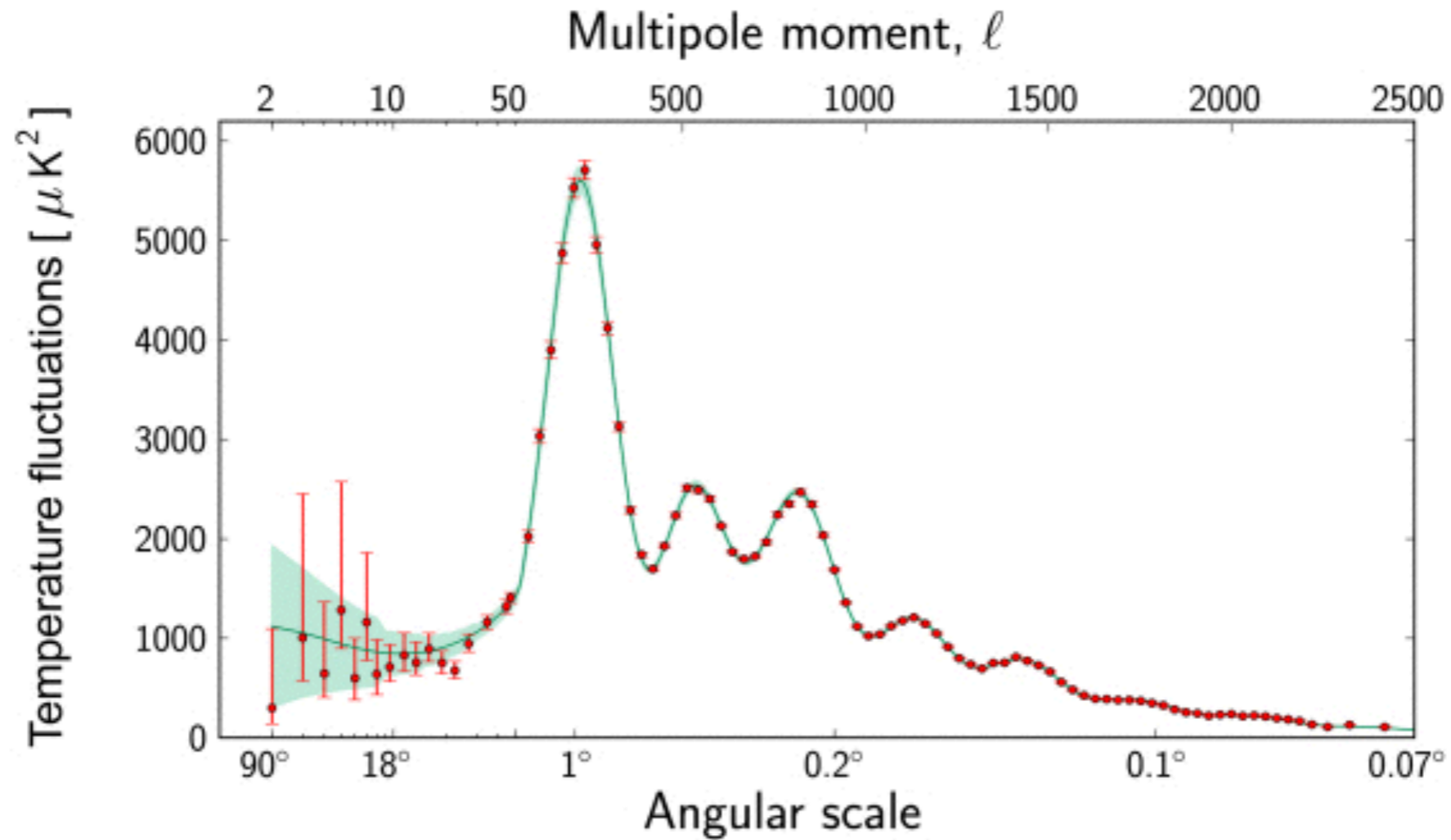
CMB angular power spectrum



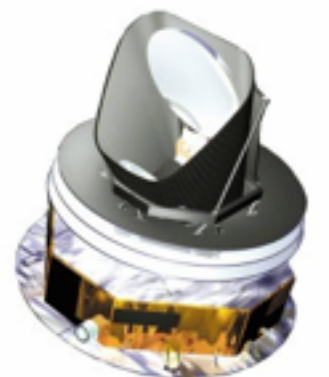
Planck



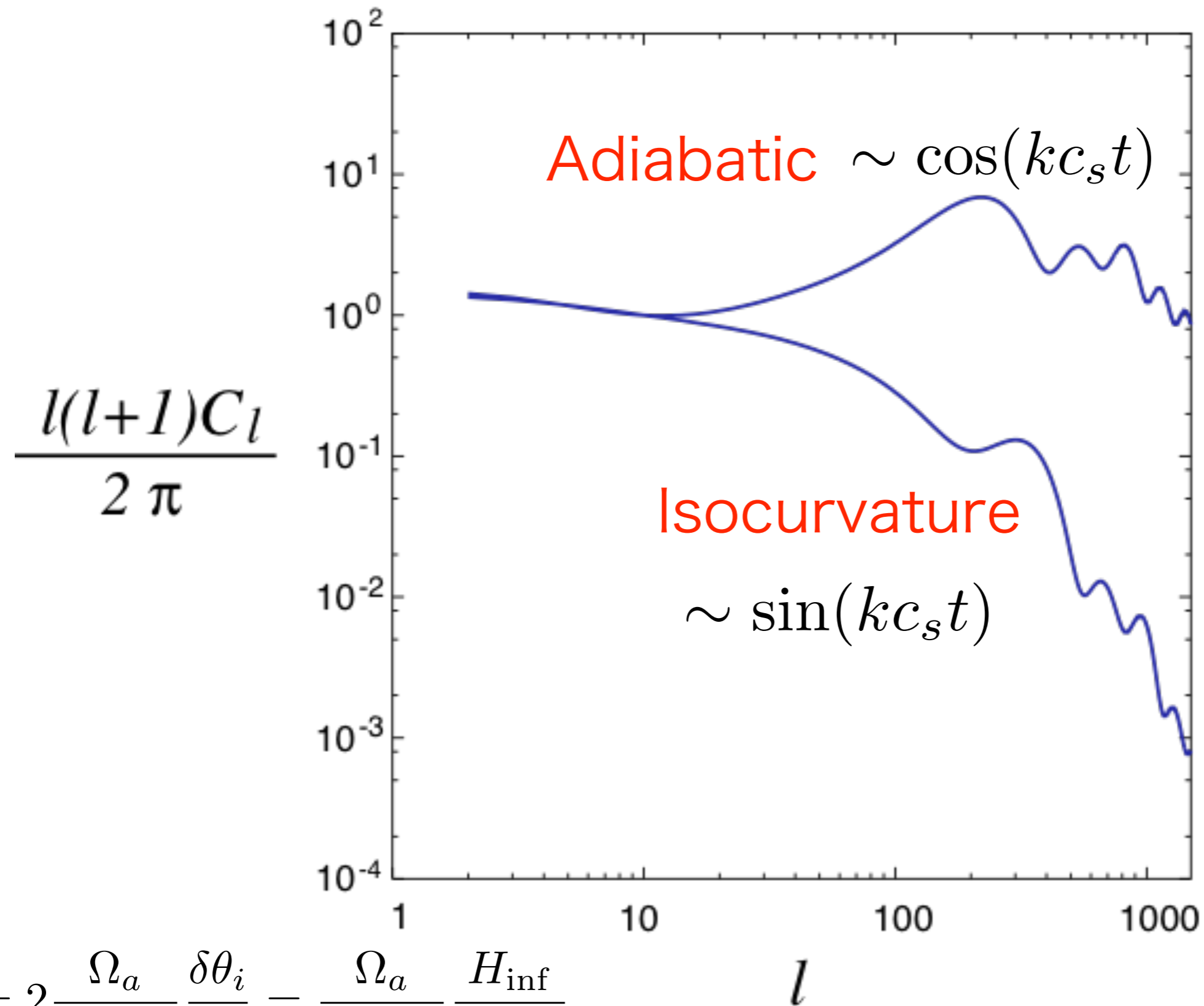
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Planck



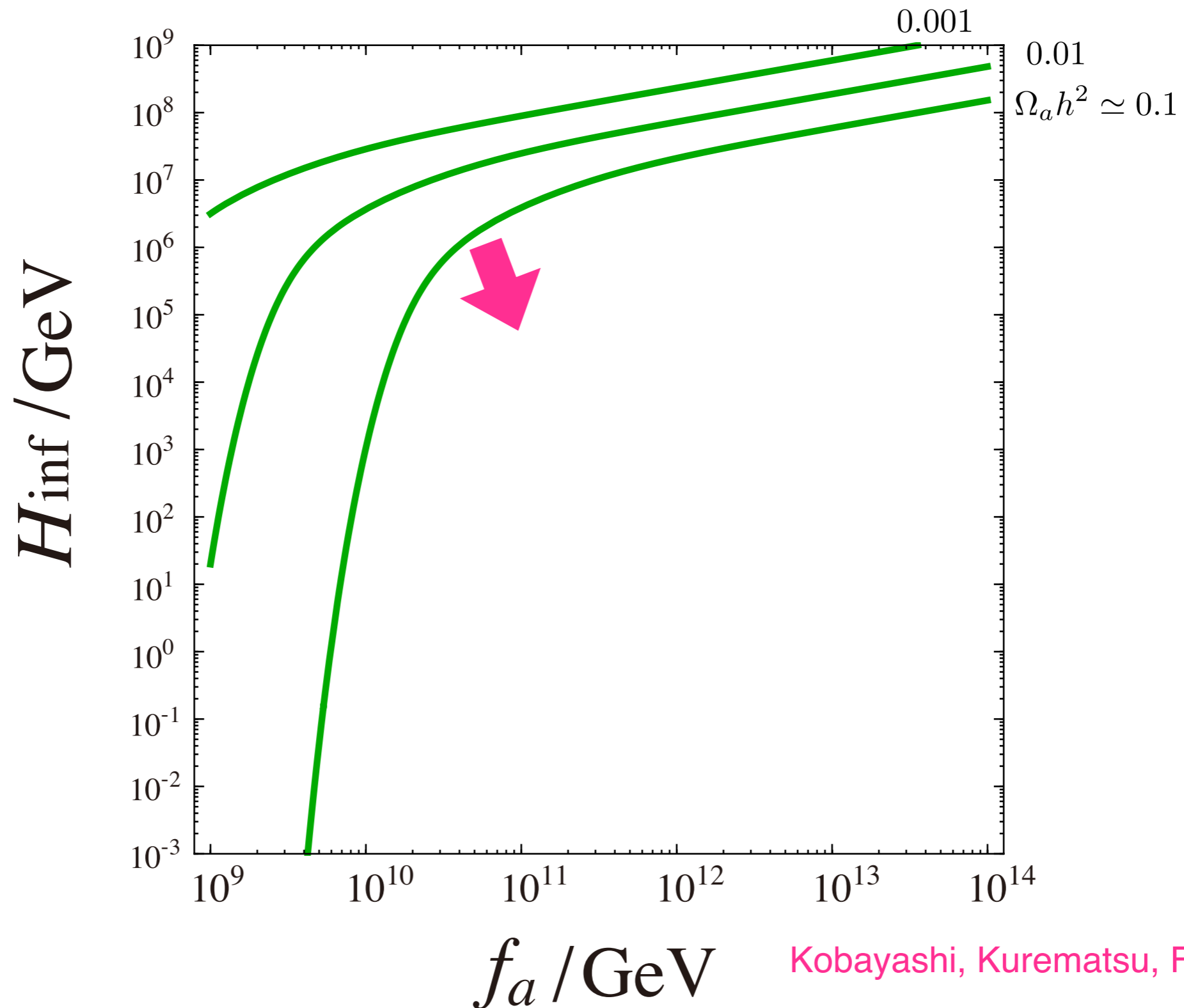
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$$S = 2 \frac{\Omega_a}{\Omega_{\text{CDM}}} \frac{\delta\theta_i}{\theta_i} = \frac{\Omega_a}{\Omega_{\text{CDM}}} \frac{H_{\text{inf}}}{\pi\theta_i f_a}$$

(Taken from Kawasaki's slide)

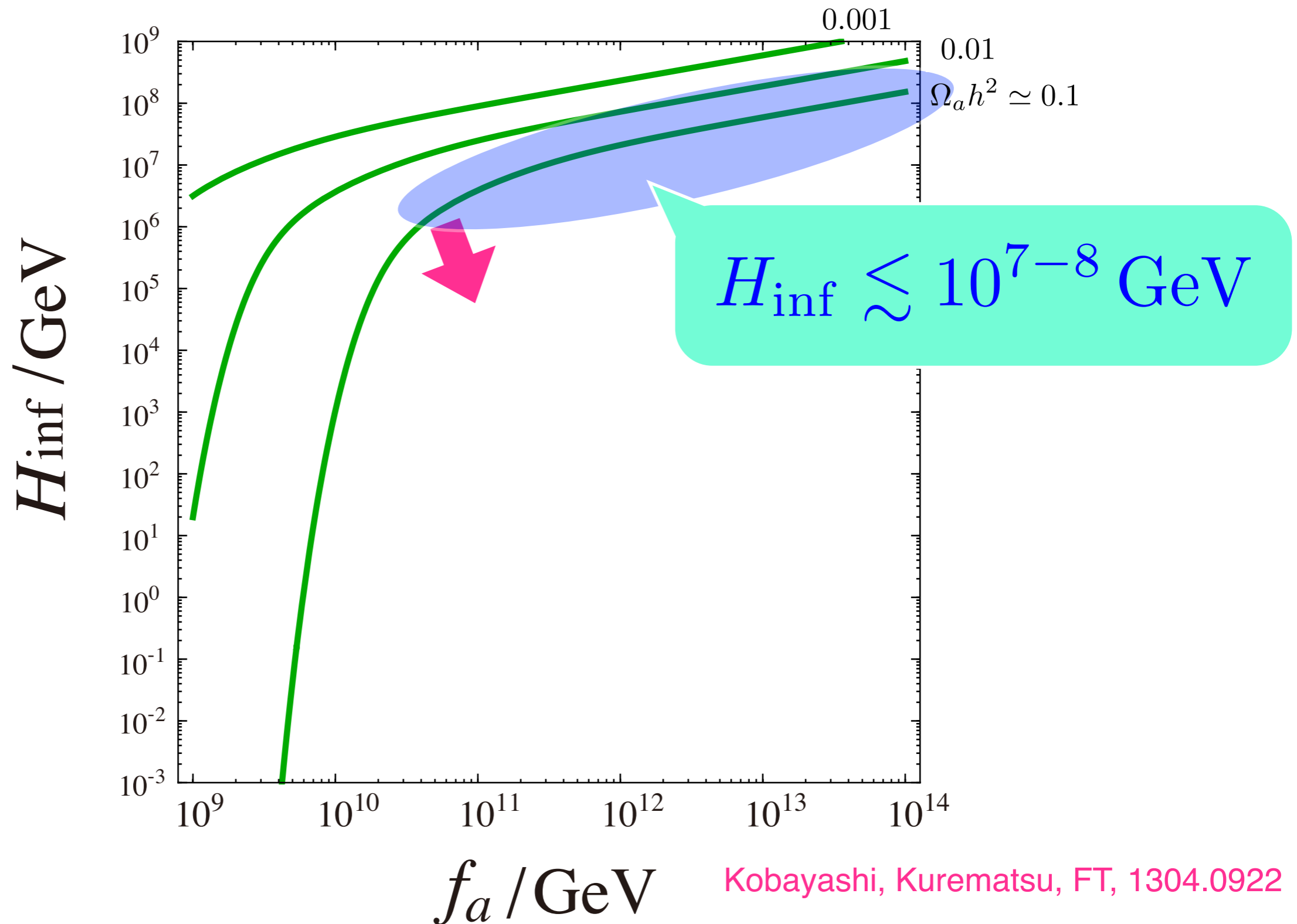
Isocurvature constraint on H_{inf}



Kobayashi, Kurematsu, FT, 1304.0922

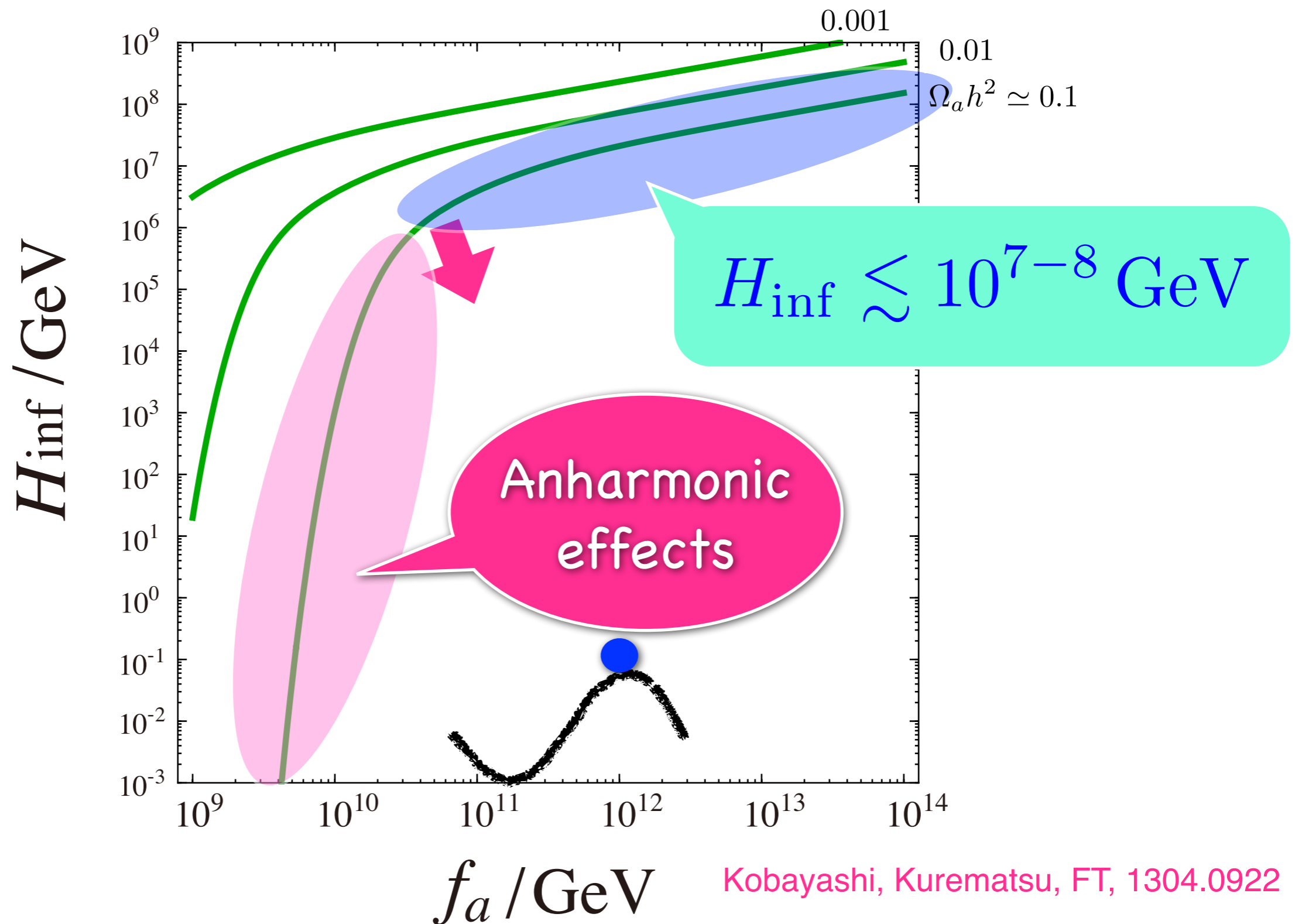
Axion DM is in severe tension w/ many inflation models!

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Solutions to isocurvature problem

1) Restoration of Peccei-Quinn symmetry during inflation.

Linde and Lyth '90 Lyth and Stewart '92

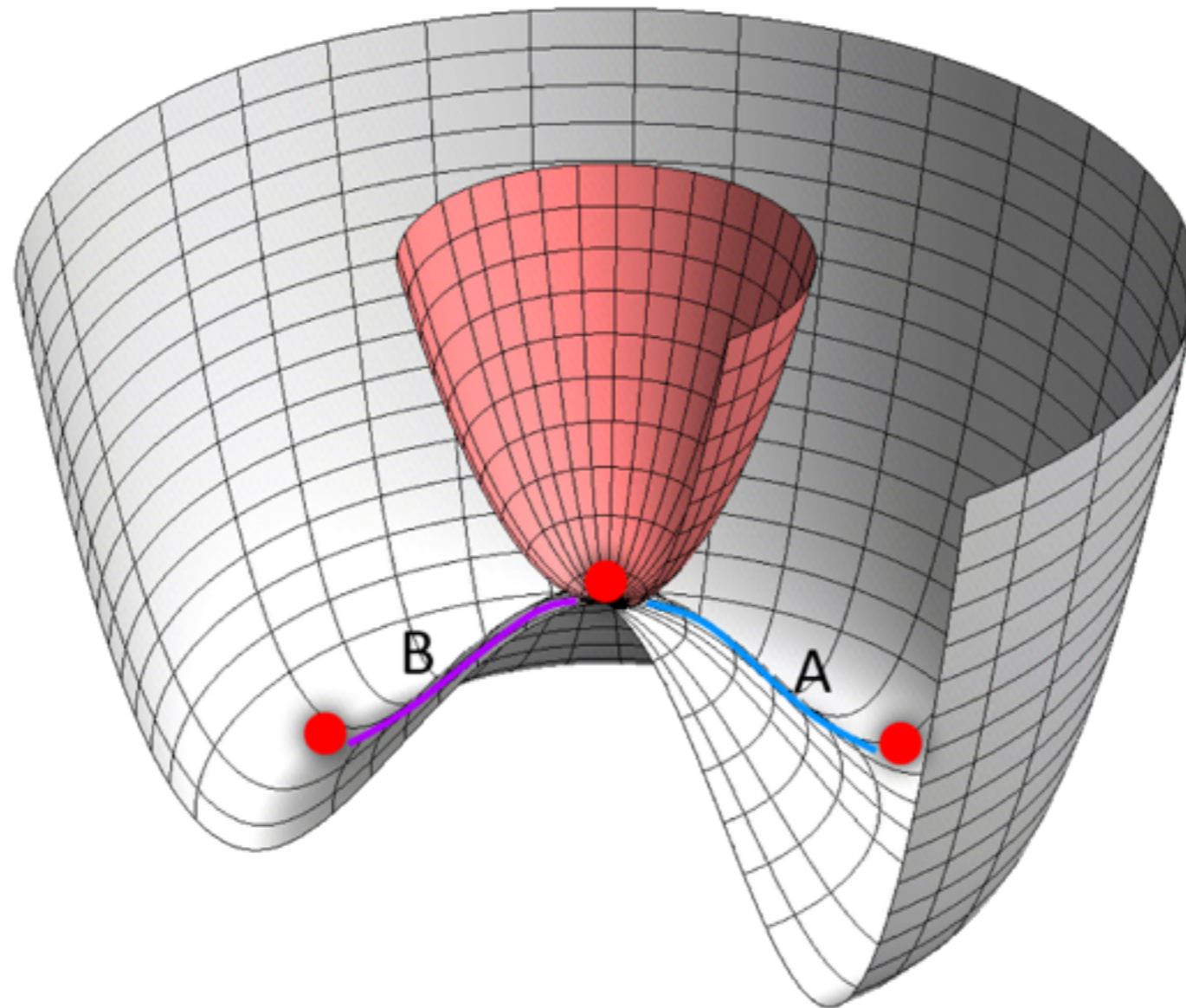


Figure taken from
M. Kawasaki's slide

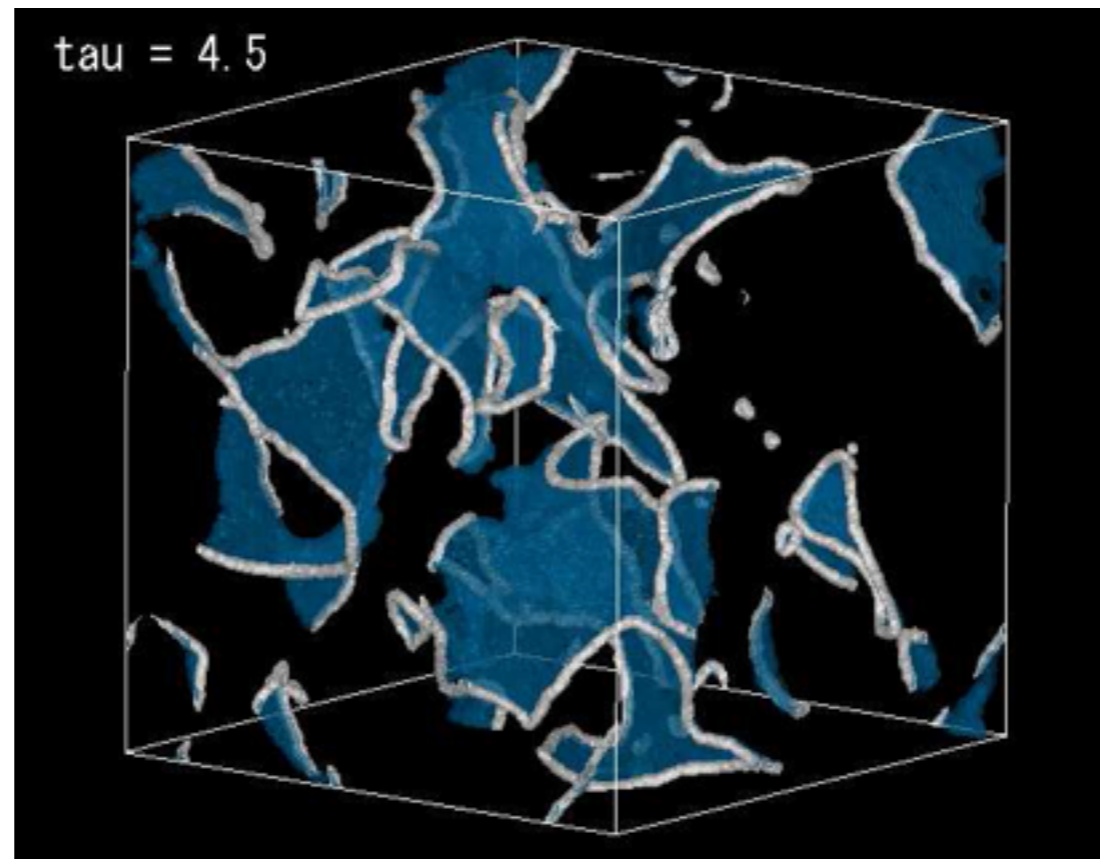
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- Axions are produced from domain walls and axion DM is possible for $f_a = 10^{10} \text{GeV}$.

Hiramatsu, Kawasaki, Saikawa and Sekiguchi, 1202.5851, 1207.3166



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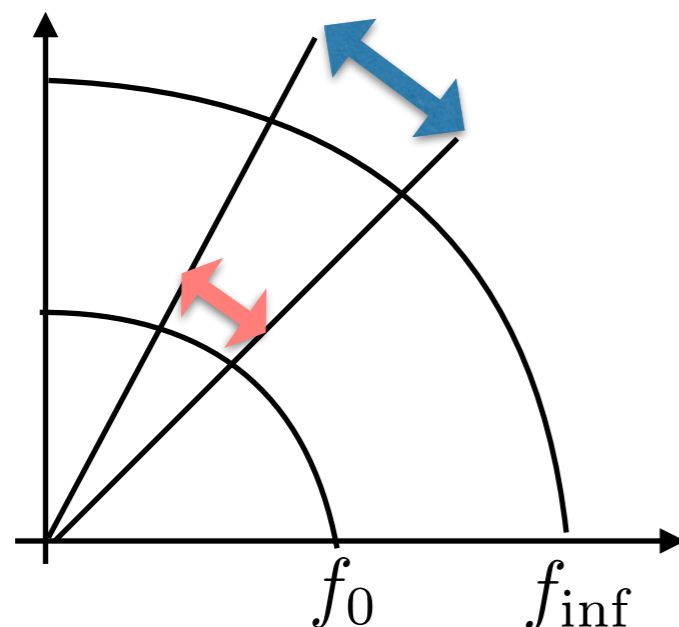
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Hiramatsu, Kawasaki, Saikawa and Sekiguchi, 1202.5851, 1207.3166

2) Dynamical axion decay constant

Linde and Lyth '90 Linde, '91



Axion: phase component
Saxion: radial component

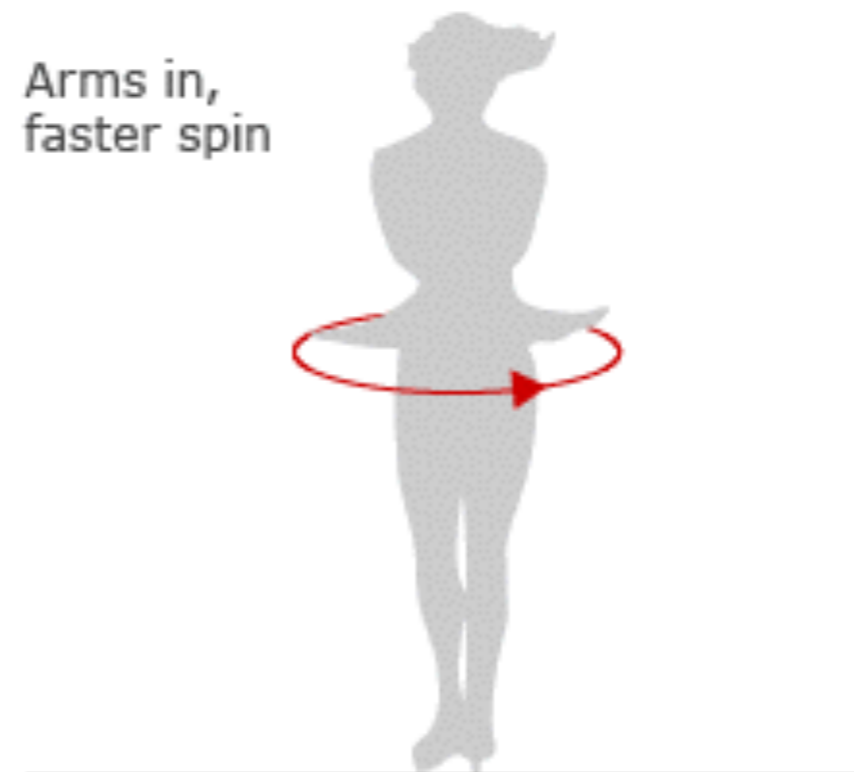
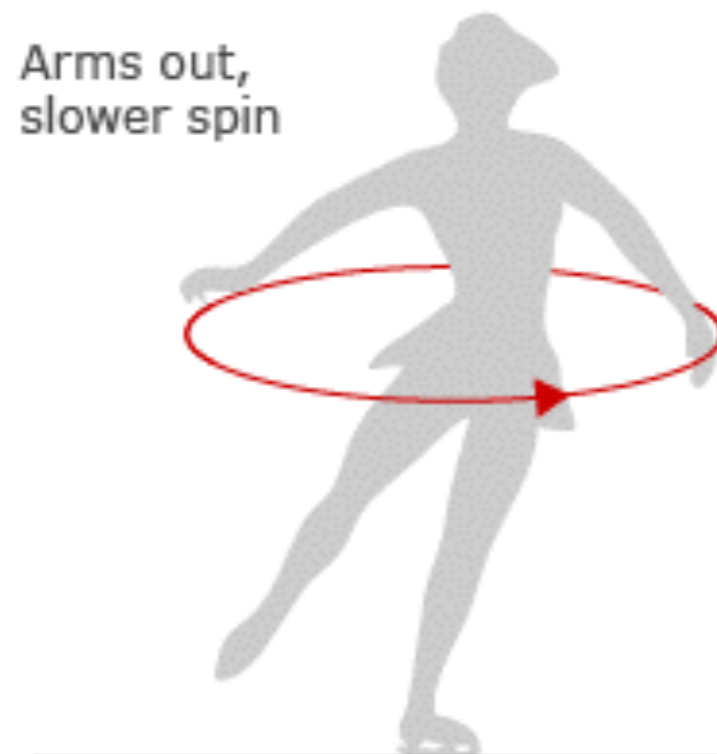
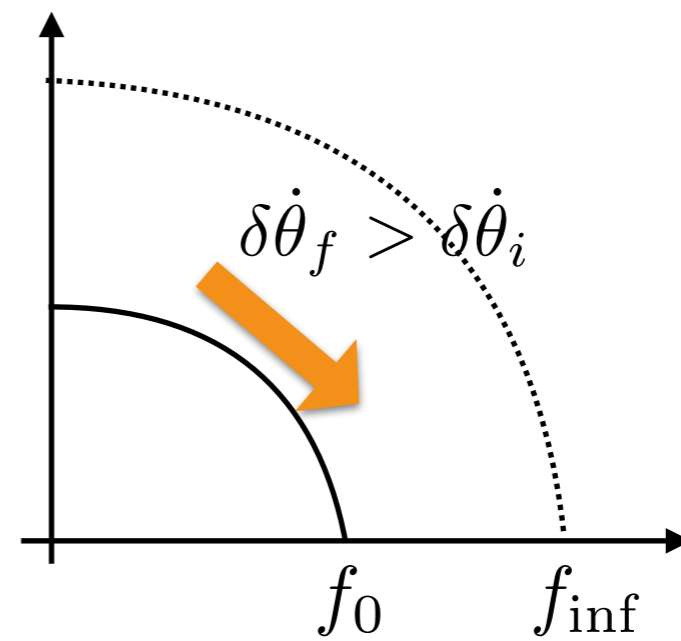
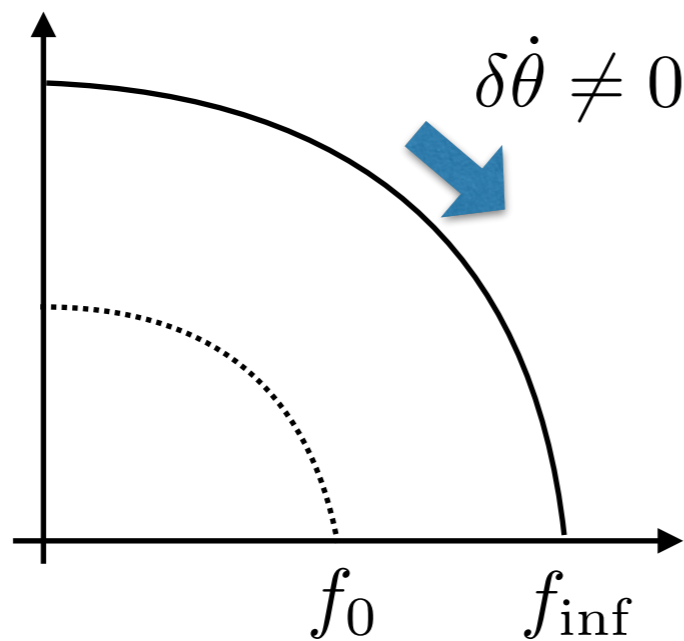
$$\Phi = \frac{f + s}{\sqrt{2}} e^{ia/f}$$

$$\delta\theta = \text{const.} \quad \longrightarrow \quad \delta a = \delta a_{\text{inf}} \left(\frac{f_0}{f_{\text{inf}}} \right)$$

At small scales, however, axion fluctuations can be enhanced significantly!

Takeshi Kobayashi, FT, 1607.04294

The enhancement of axion fluctuations at small scales can be understood by noting that “angular momentum” is conserved when the decay constant changes.

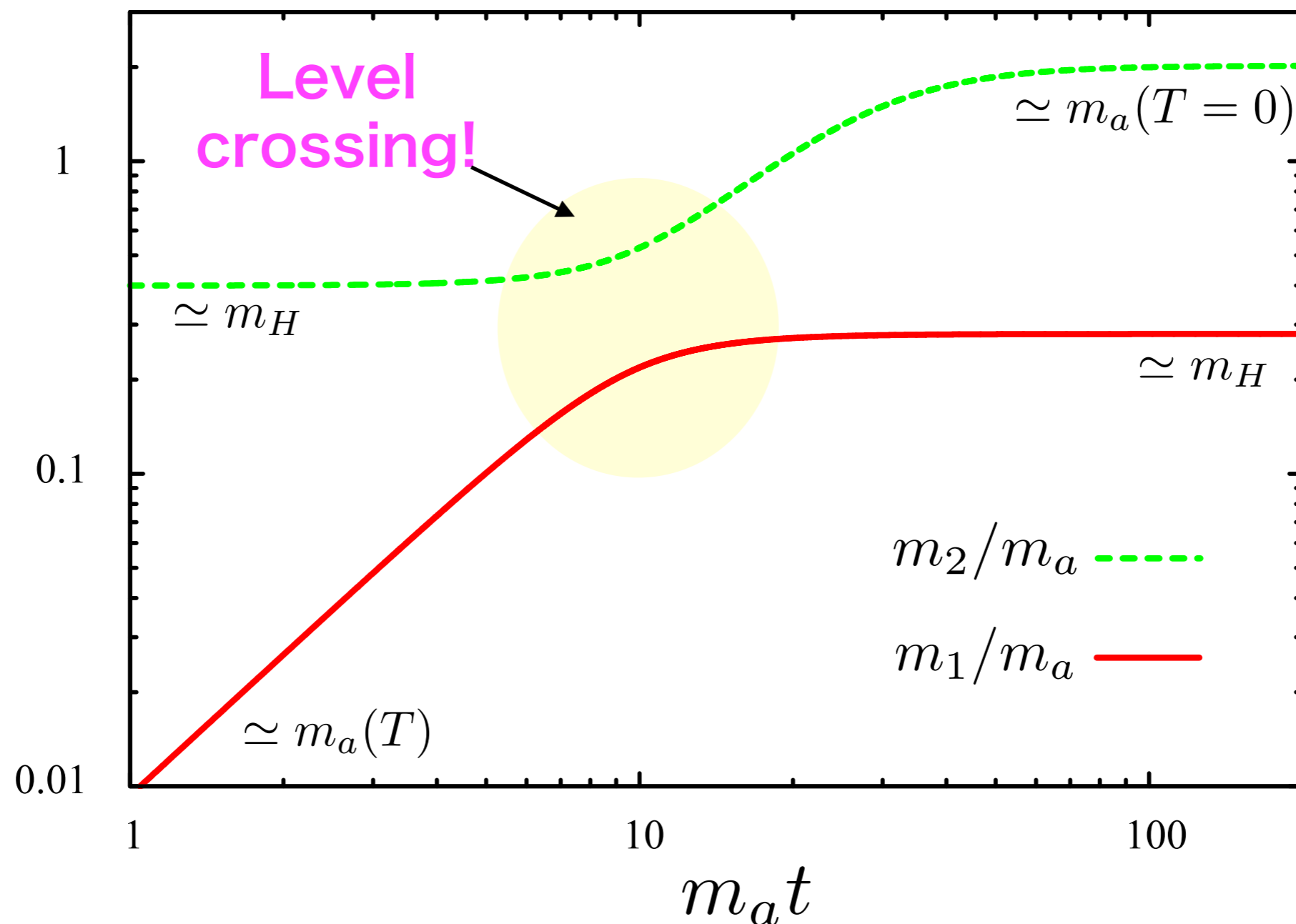


Solutions to isocurvatures problem

3) MSW-like resonance btw. axion and ALP.

Hill, Ross '88, Kitajima, FT 1411.2011

The level crossing necessarily occurs if $m_H^2 < m_a^2(T=0)$.

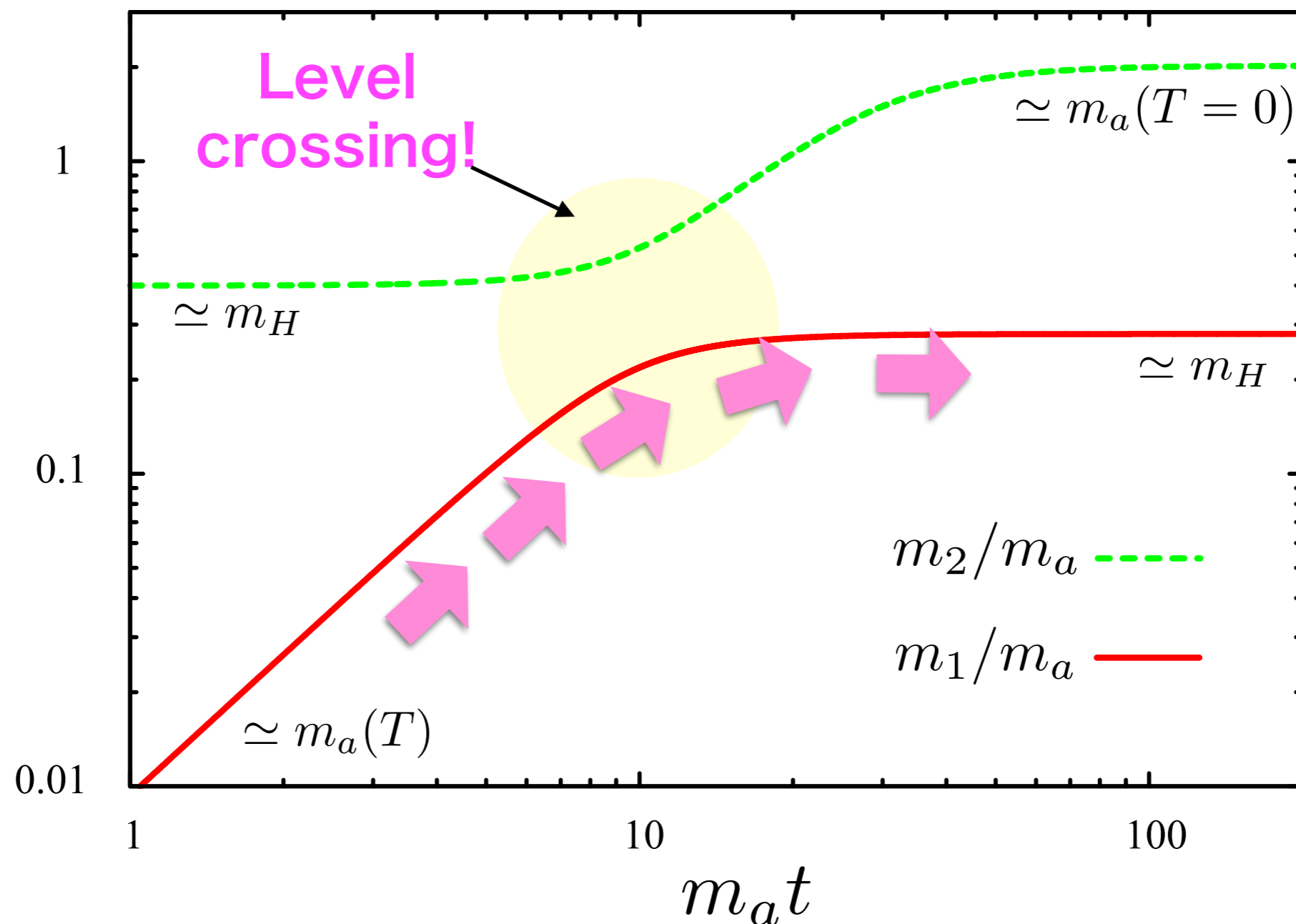


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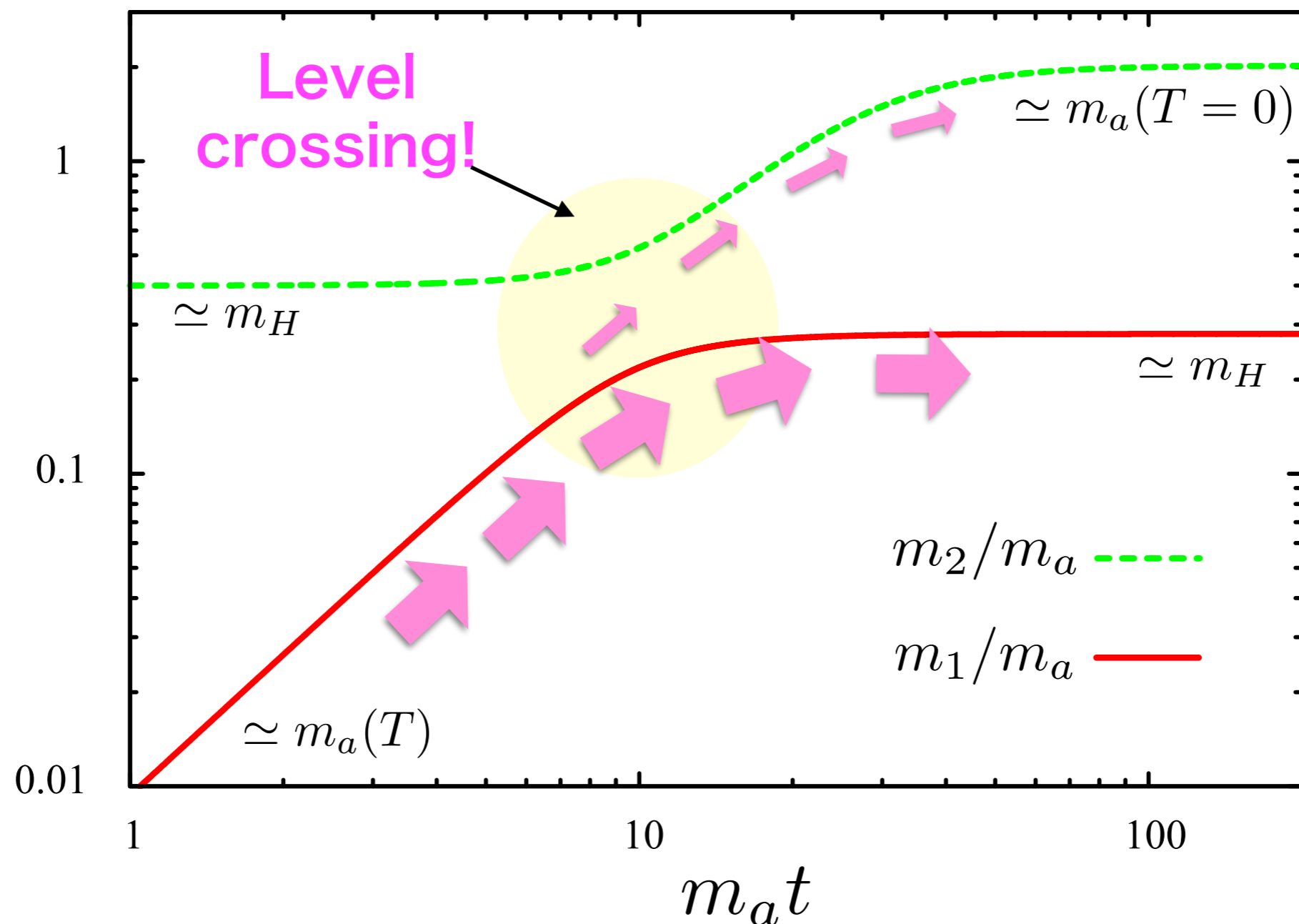


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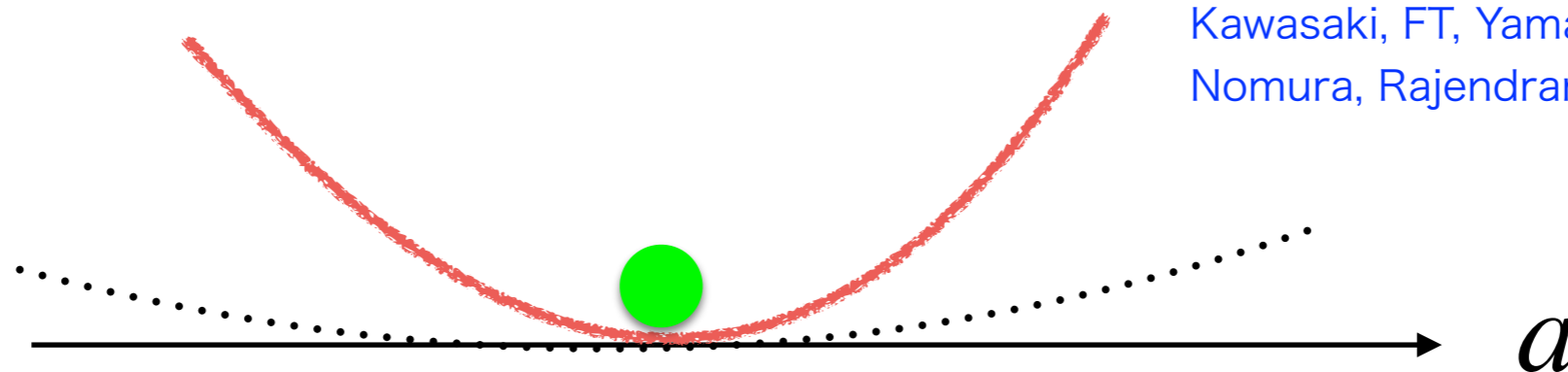
4) Heavy axions during inflation $m_a^2 \gtrsim H_{\text{inf}}^2$

- Stronger QCD during inflation

cf. Dvali, '95, Jeong, FT 1304.8131
Choi et al, 1505.00306

- Extra explicit PQ breaking
e.g. Witten effect

Dine, Anisimov hep-ph/0405256
Higaki, Jeong, FT, 1403.4186,
Barr and J.E.Kim, 1407.4311
FT and Yamada 1507.06387
Kawasaki, FT, Yamada 1511.05030
Nomura, Rajendran, Sanches, 1511.06347

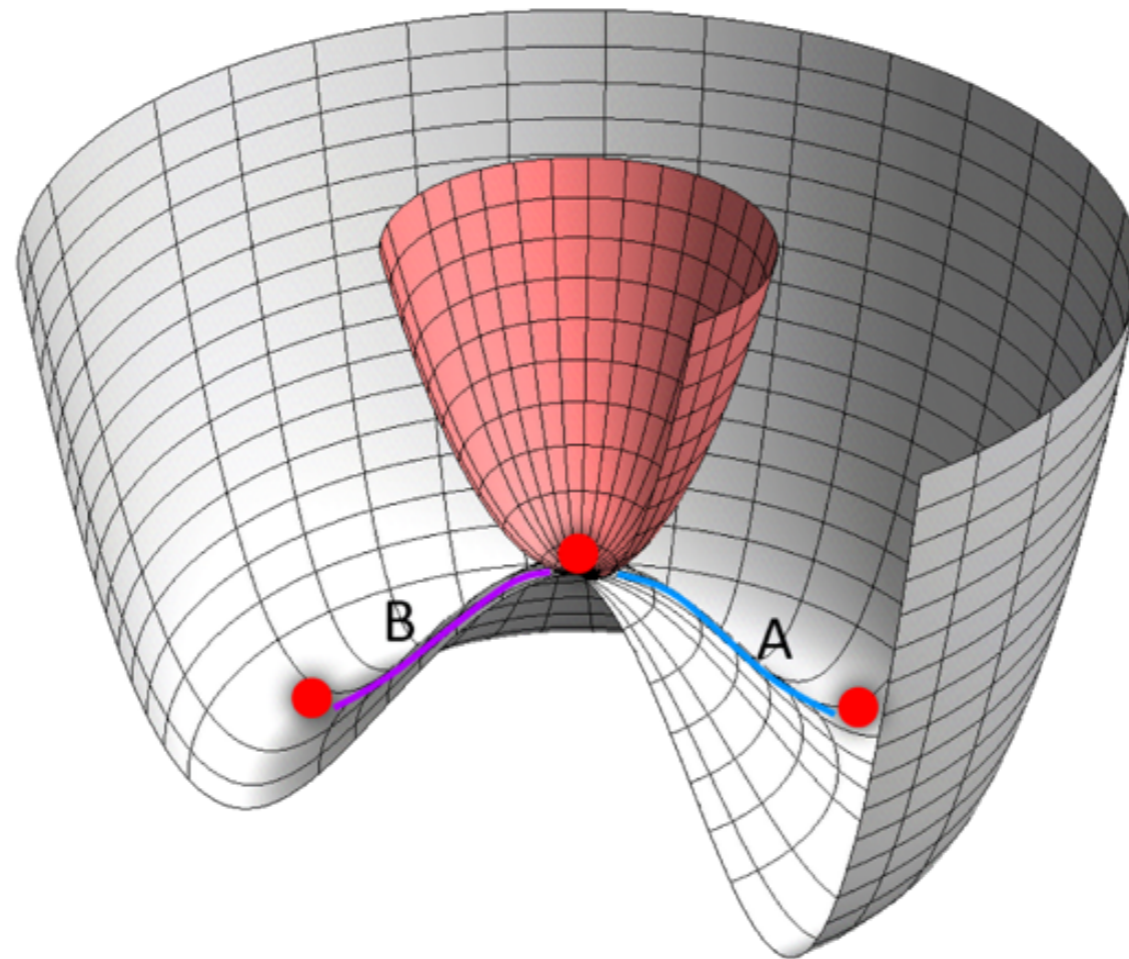


The extra PQ breaking term must be sufficiently suppressed at present.

Aligned QCD axion

Higaki, Jeong, Kitajima, FT, 1512.05295, 1603.02090,
Higaki, Jeong, Kitajima, Sekiguchi, FT, 1606.05552

No axion isocurvature perturbations if the PQ symmetry is restored during or after inflation.



Is high T_R or H_{inf} necessary?

$$T_R, H_{inf} \gtrsim F_a$$

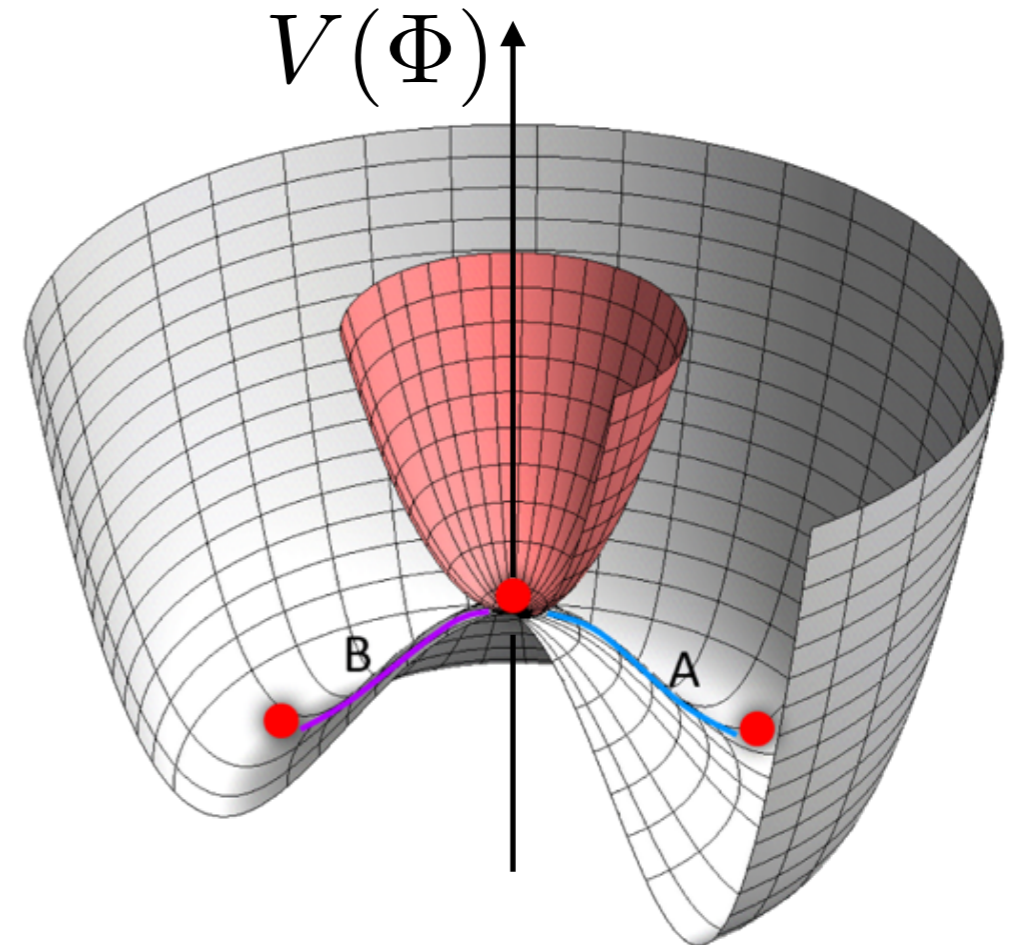
Classical axion window:
 $10^9 \text{ GeV} \lesssim F_a \lesssim 10^{12} \text{ GeV}$

Decay constant = PQ breaking scale?

In a simple set-up,

$$\langle \Phi \rangle \sim F_a$$

Φ : PQ scalar



However, this is not necessarily the case.

If there are multiple PQ scalars,

$$\langle \Phi \rangle \ll F_a$$

is possible.

Alignment mechanism

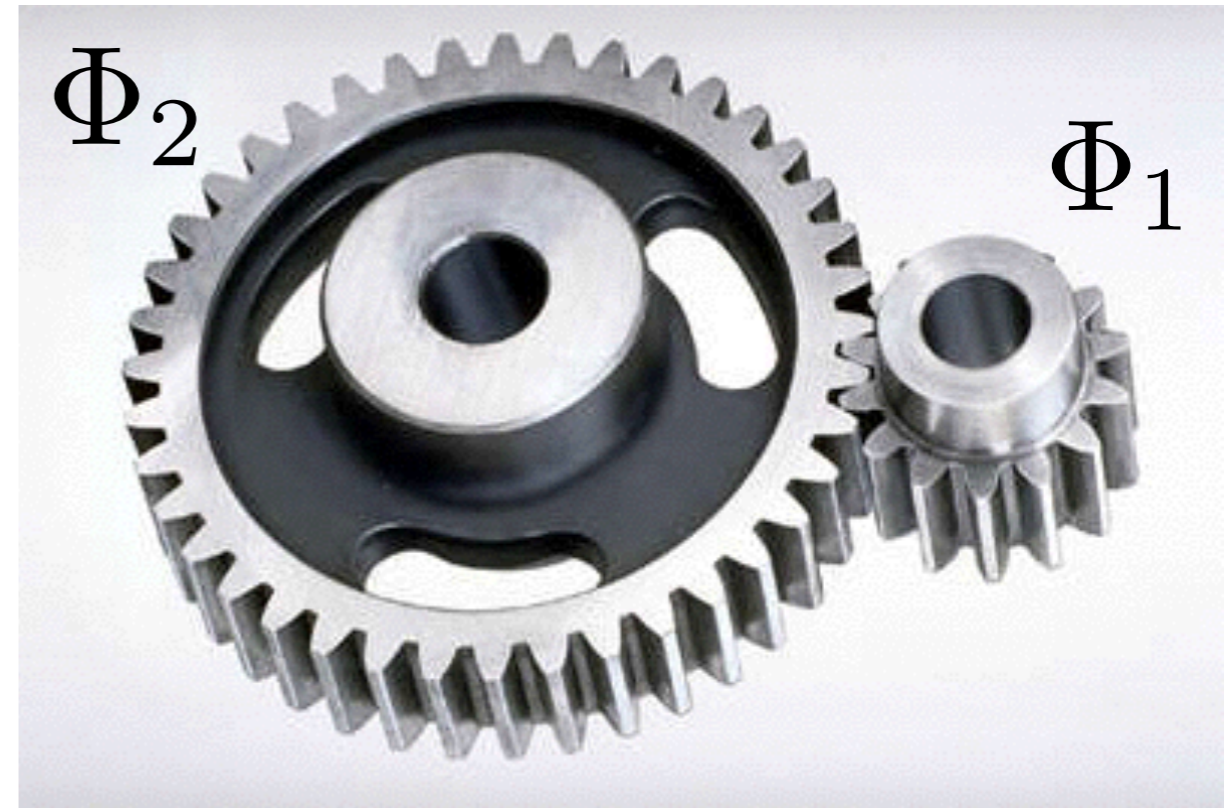
The decay constant can be enhanced by the largest hierarchy among the PQ charges in the alignment mechanism,

See also Sikivie '86 Kim, Nilles, Peloso, hep-ph/0409138 Choi, Kim, Yun, 1404.6209, Higaki, FT, 1404.6923 Harigaya and Ibe, 1407.4893, Choi and Im, 1511.00132, Kaplan and Rattazzi, 1511.01827.

Clockwork axion model with N=2:

$$V = \sum_{i=1}^2 (-m_i^2 |\Phi_i|^2 + \lambda_i |\Phi_i|^4) + \epsilon (\Phi_1 \Phi_2^3 + \text{h.c.})$$

$$\Phi_i = \frac{f_i + s_i}{\sqrt{2}} e^{i a_i / f_i}$$



$$f_a = \sqrt{3^2 f_1^2 + f_2^2}, \quad a = \frac{3 f_1 a_1 - f_2 a_2}{f_a}$$

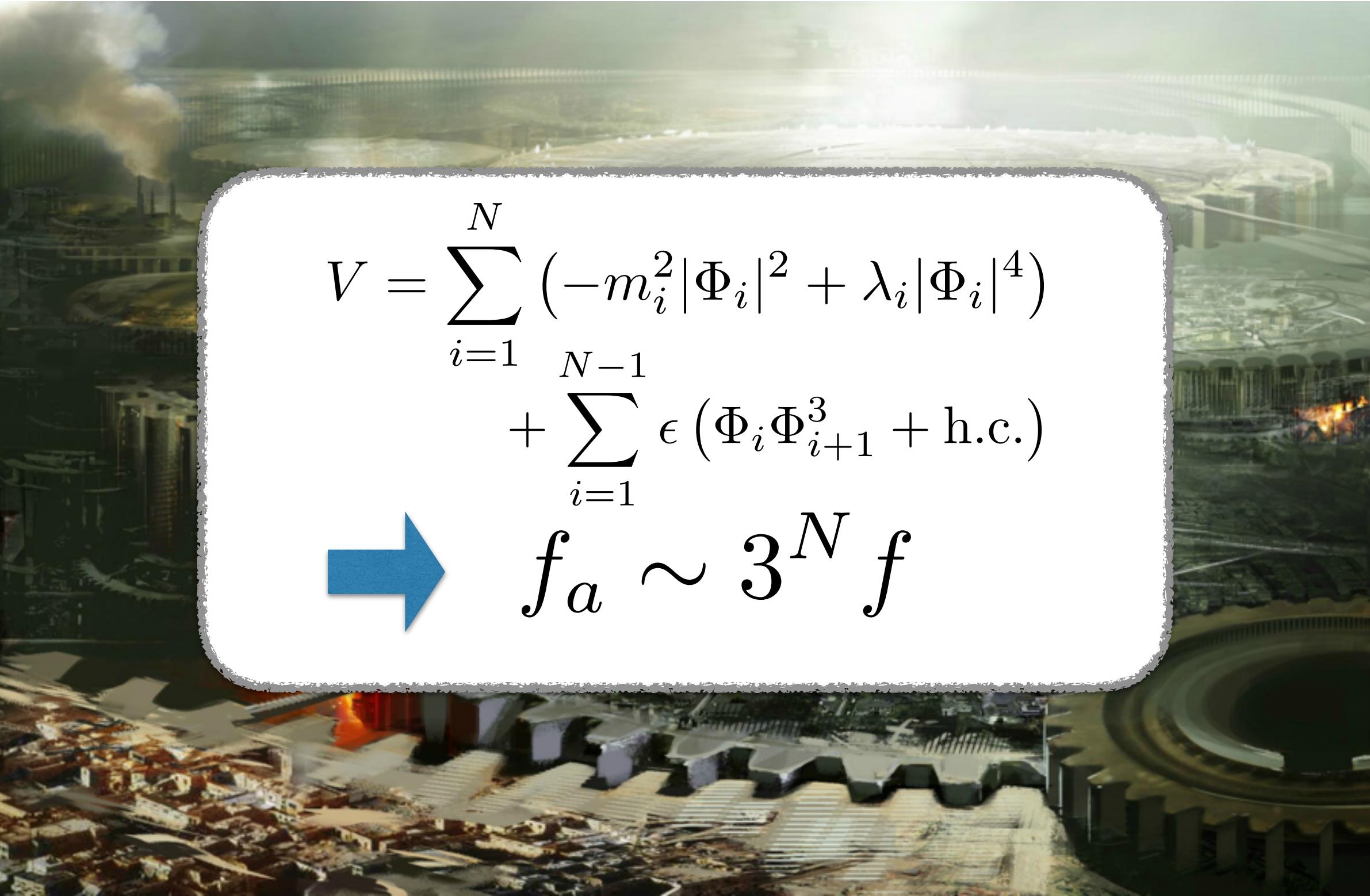
Alignment with multiple axions

Choi, Kim, Yun, 1404.6209, Higaki, FT, 1404.6923
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$$V = \sum_{i=1}^N \left(-m_i^2 |\Phi_i|^2 + \lambda_i |\Phi_i|^4 \right) + \sum_{i=1}^{N-1} \epsilon \left(\Phi_i \Phi_{i+1}^3 + \text{h.c.} \right)$$

→ $f_a \sim 3^N f$

Aligned QCD axion

In general, if we have

$$V(a_i) = - \sum_{i=1}^{N-1} \Lambda_i^4 \cos \left(\frac{a_i}{f_i} + n_i \frac{a_{i+1}}{f_{i+1}} \right),$$

$N-1$ of the N axions becomes massive, leaving one massless mode, a .

$$a = \frac{1}{f_a} \sum_{i=1}^N (-1)^{i-1} \left(\prod_{j=i}^N n_j \right) f_i a_i, \quad \text{with} \quad f_a^2 = \sum_{i=1}^N \left(\prod_{j=i}^N n_j^2 \right) f_i^2,$$

Choi, Kim, Yun, 1404.6209,

Adding a coupling to the PQ quarks

$$\Delta \mathcal{L} = y_q \Phi_N \bar{Q} Q.$$

a becomes the QCD axion with $F_a = f_a \sim 3^N f$ for $f_i = f$

**There are many axions and saxions at f (e.g. at TeV scale)
much lower than the conventional axion window!**

Higaki, Kitajima, FT, 1408.3936 , Higaki, Jeong, Kitajima, FT, 1512.05295.

Quality of $U(1)_{PQ}$

Higaki, Jeong, Kitajima, FT, 1512.05295, 1603.02090,

In the conventional scenario, one needs to suppress PQ breaking terms up to high order

Carpenter, Dine, Festuccia, '09

$$\text{e.g. } \frac{\Phi^{n+4}}{M_p^n} \quad n > 10 \quad \text{for} \quad \langle \Phi \rangle \sim F_a \sim 10^{12} \text{ GeV}$$

In the aligned QCD axion models, the PQ symmetry breaking scale is much smaller,

$$\langle \Phi_i \rangle \ll F_a$$

which relaxes the required high quality of the PQ symmetry.

Topological defects

Higaki, Jeong, Kitajima, Sekiguchi, FT, 1606.05552

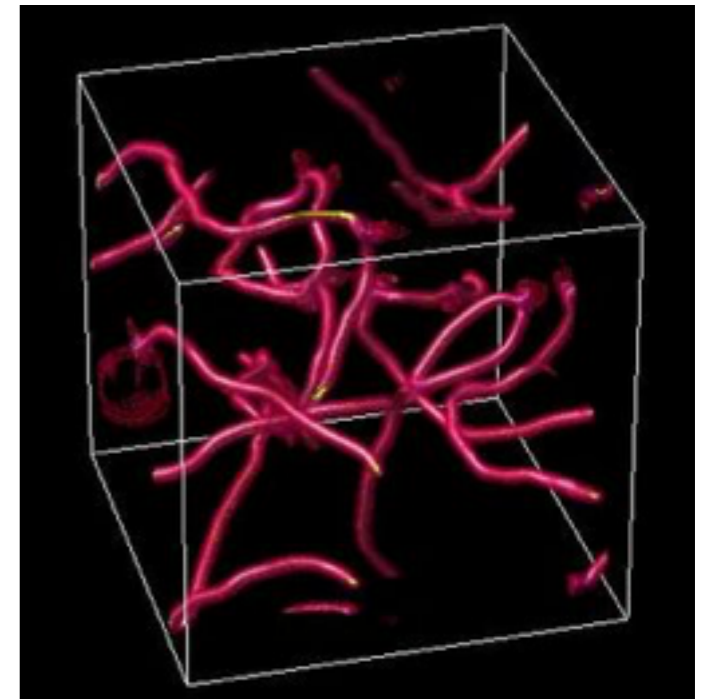
Cosmic strings appear when the PQ symmetry is broken, and their tension is dominated by the gradient energy outside the core.

$$\Phi = \frac{f}{\sqrt{2}} e^{i\theta} \quad \text{in cylindrical coordinate}$$

$$\mu \sim \mu_{\text{core}} + \int_{\delta}^R \left| \frac{1}{r} \frac{\partial \Phi}{\partial \theta} \right|^2 2\pi r dr \approx \pi f^2 \ln \left(\frac{R}{\delta} \right),$$

R : distance b/w strings

δ : core radius



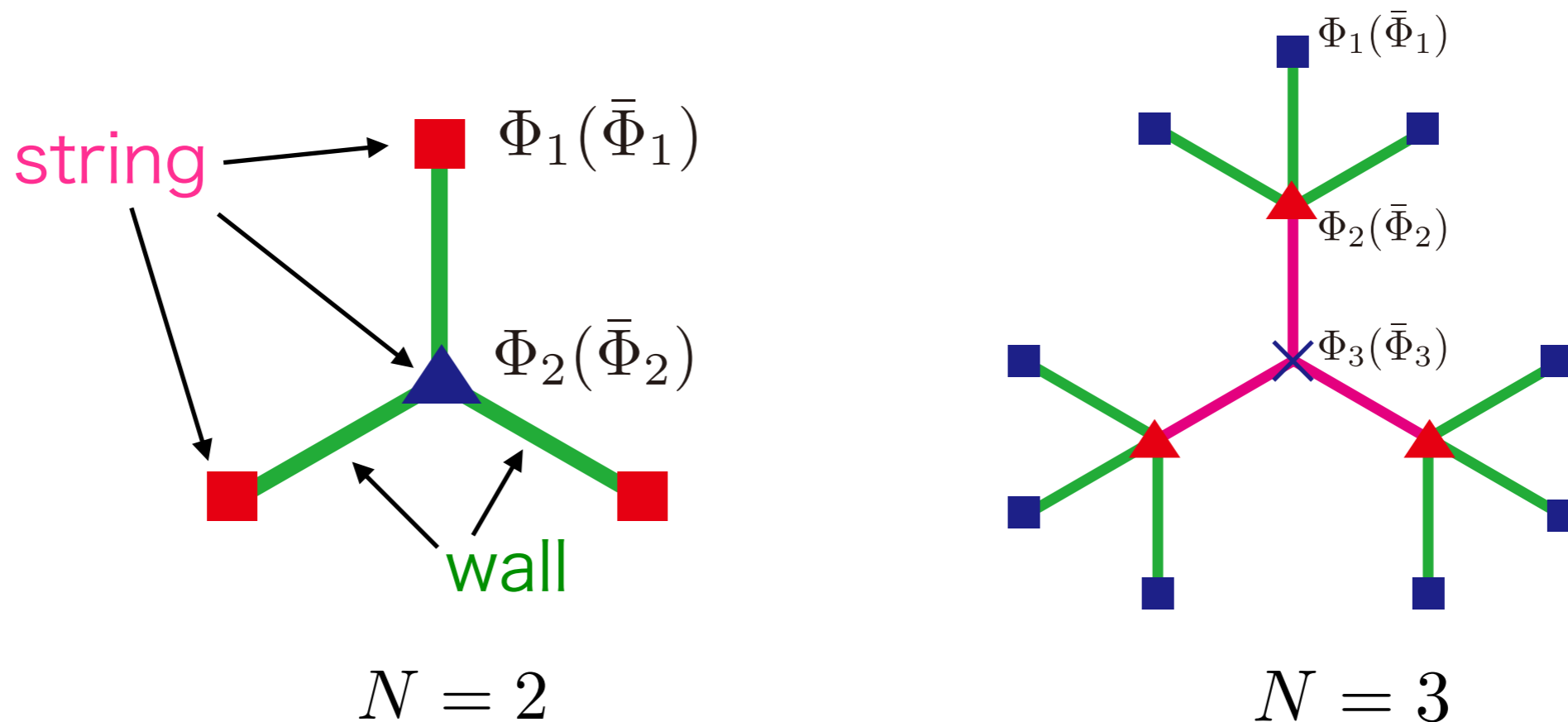
(credit: M. Hindmarsh)

In the aligned QCD axion, the tension of each string is of order f^2 , much smaller than F_a^2 . Any correspondence between the two?

Topological defects

Higaki, Jeong, Kitajima, Sekiguchi, FT, 1606.05552

There is an isolated string-wall solution, “string bundle”,
i.e., many strings glued by domain walls:

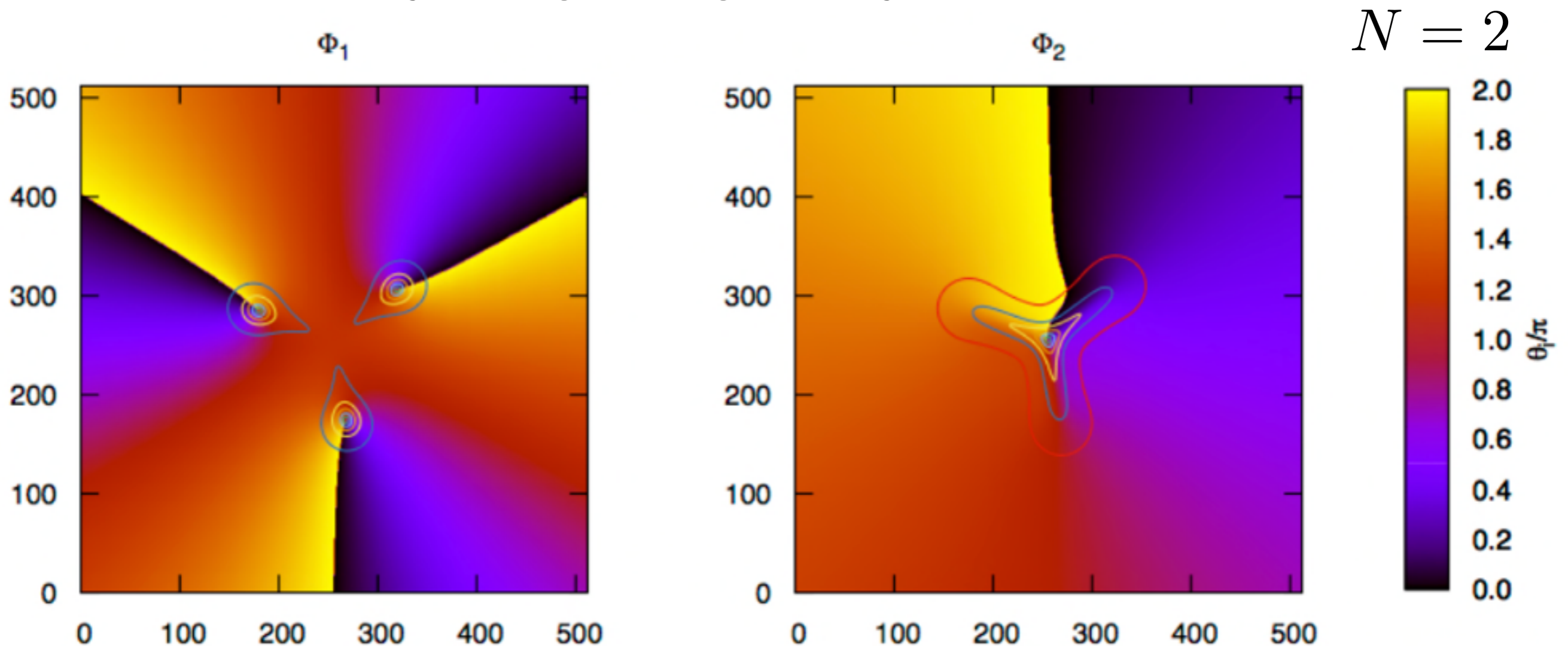


The aligned structure in the field space
exhibits itself in the real space!

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There is an isolated string-wall solution, “string bundle”, where many strings are glued by domain walls:

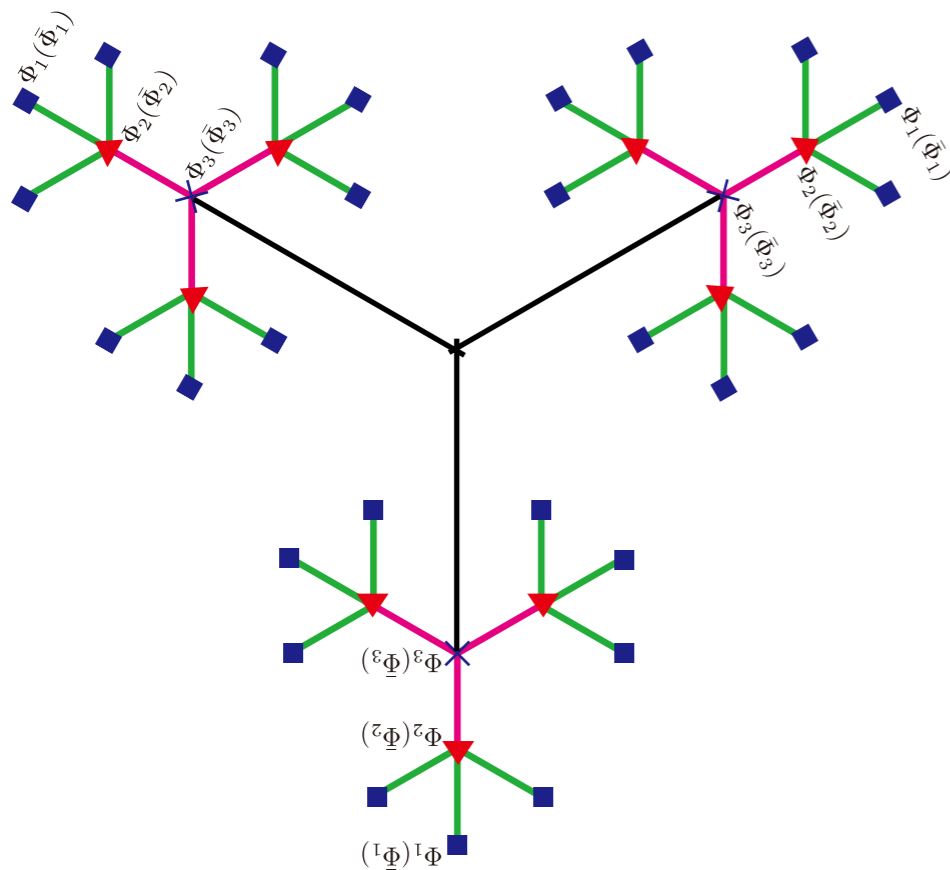


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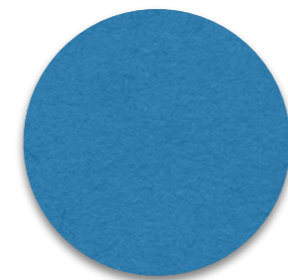
Topological defects

Higaki, Jeong, Kitajima, Sekiguchi, FT, 1606.05552

The tension of the isolated string-wall system is equal to that of a single PQ field.



21

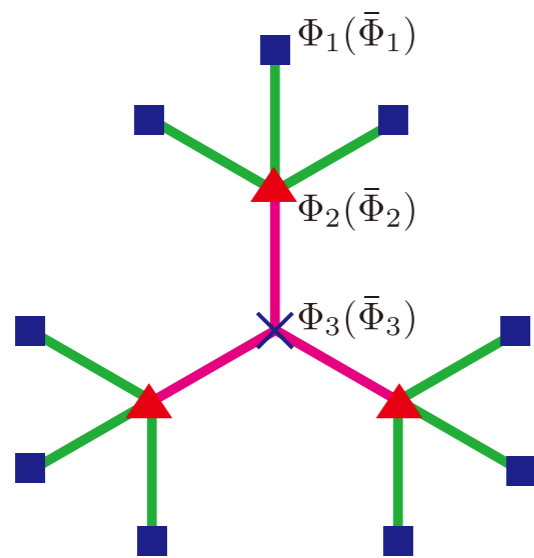


$$\mu_{\text{eff}} \simeq \pi(3^{2(N-1)} f_1^2 + \cdots + 3^2 f_{N-1}^2 + f_N^2) \ln \left(\frac{R}{\delta} \right) = \pi F_a^2 \ln \left(\frac{R}{\delta} \right)$$

Topological defects

Higaki, Jeong, Kitajima, Sekiguchi, FT, 1606.05552

For large N , however, such isolated string bundles are probably not produced in the Universe, as they require exponentially large hierarchy in the cosmic string distribution.



$$|\#(S_i) - \#(\bar{S}_i)| = 3^{N-i}$$

Initial condition,
or scaling law:

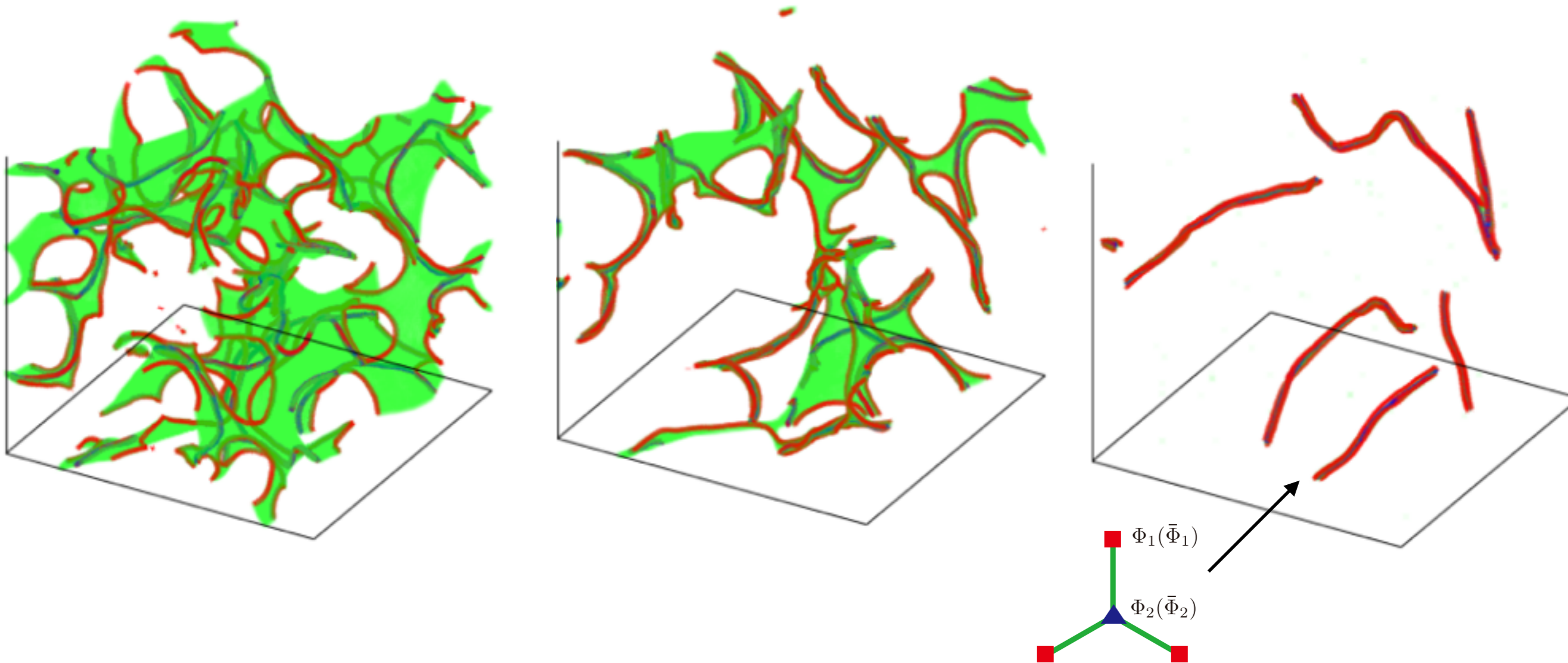
$$|\#(S_i) - \#(\bar{S}_i)| = \mathcal{O}(1).$$

The string-wall network will be infinitely large.

Numerical simulation

Higaki, Jeong, Kitajima, Sekiguchi, FT, 1606.05552

$$N = 2$$

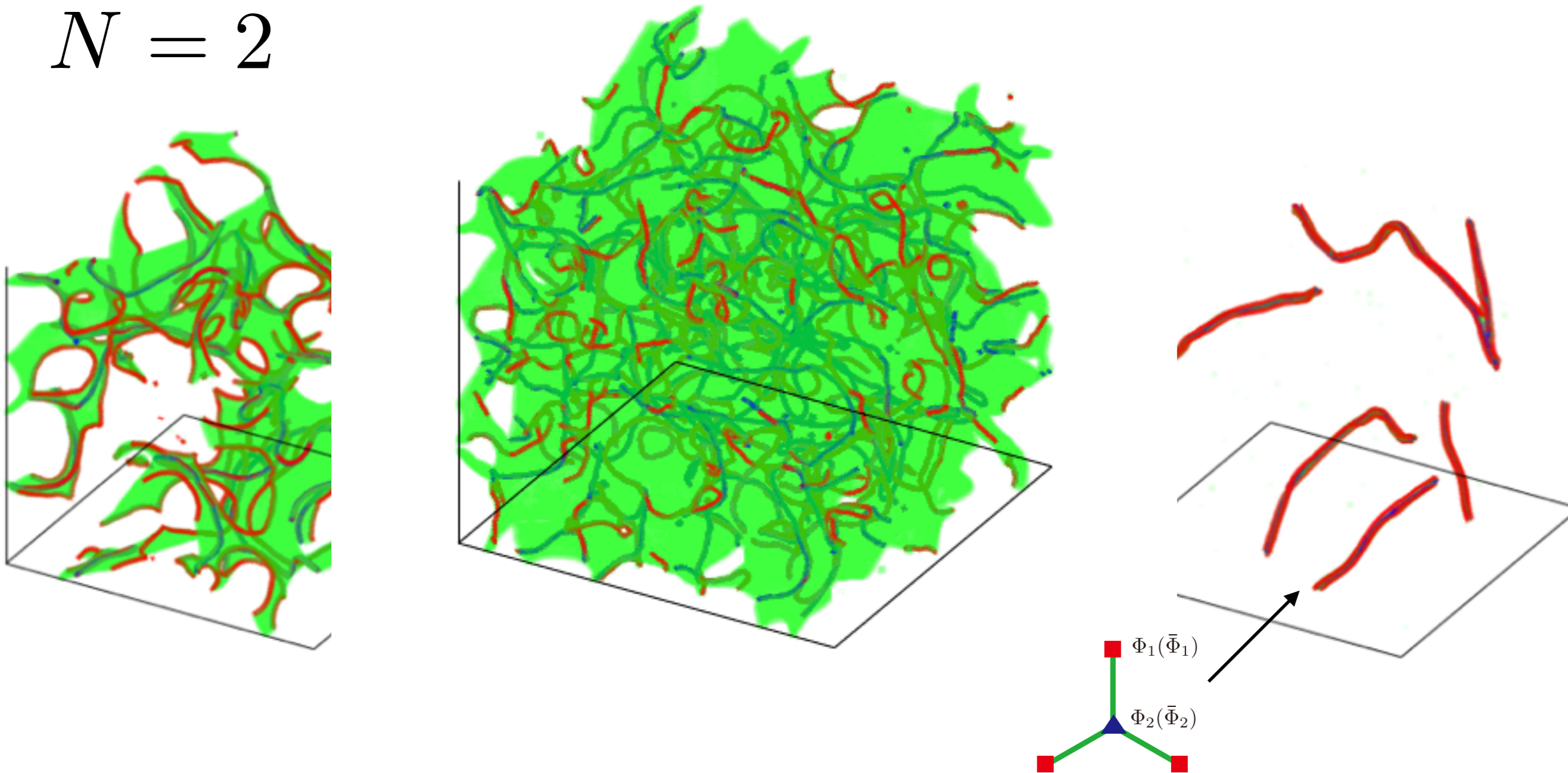


Strings glued by walls remain, and domain walls disappear in the case of $N=2$.

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Hinaki Isono, Kitaiima, Sekiguchi, FT, 1606.05552

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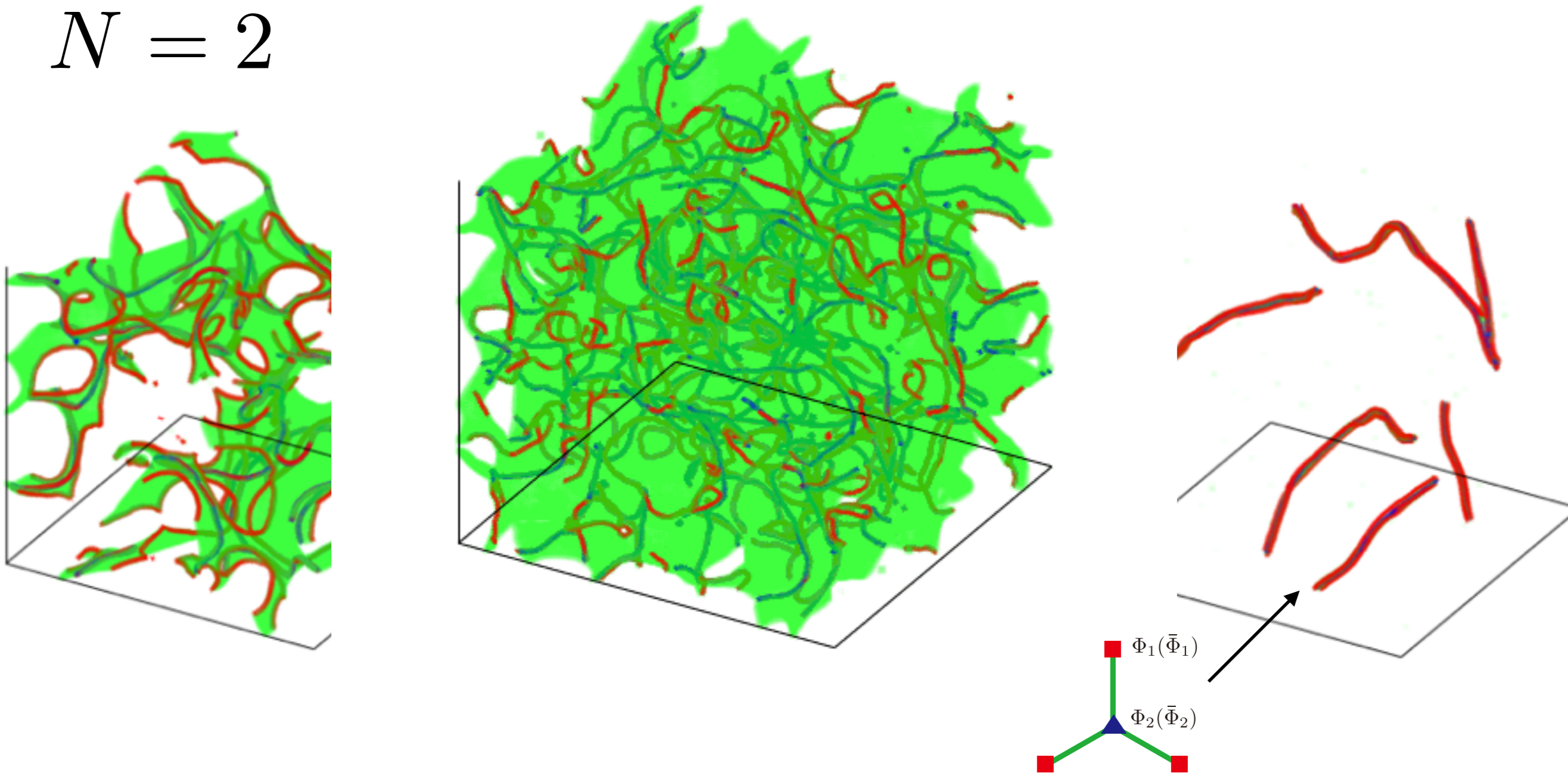


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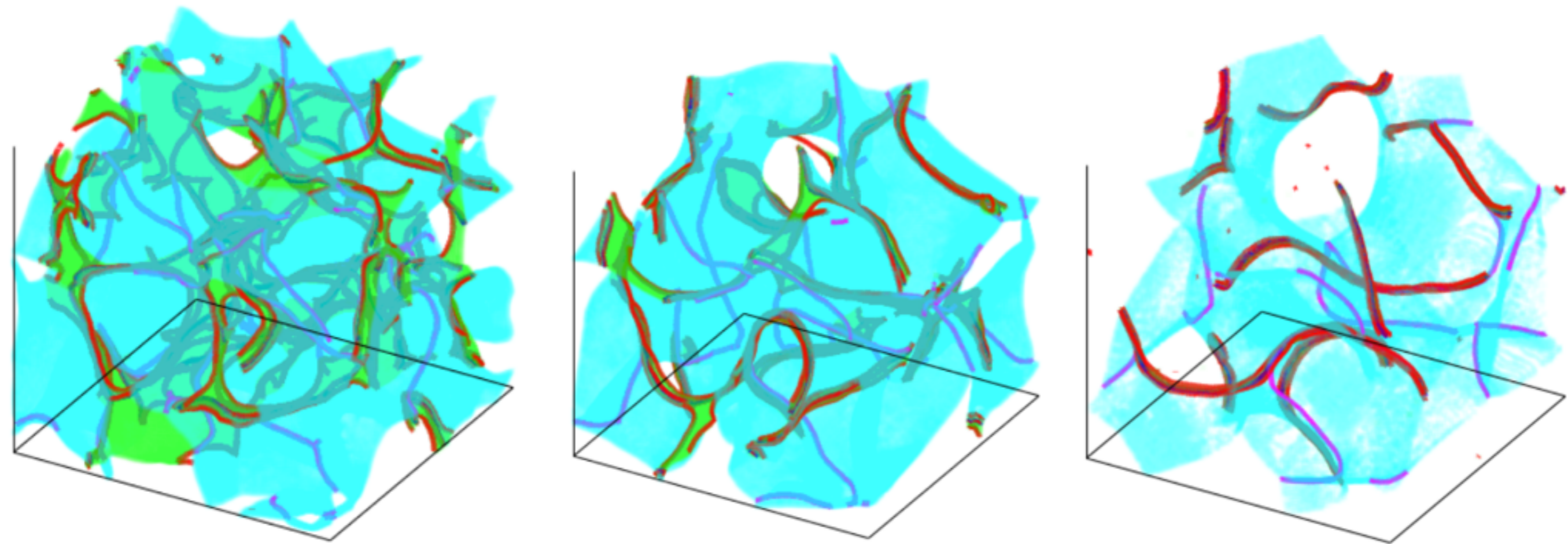


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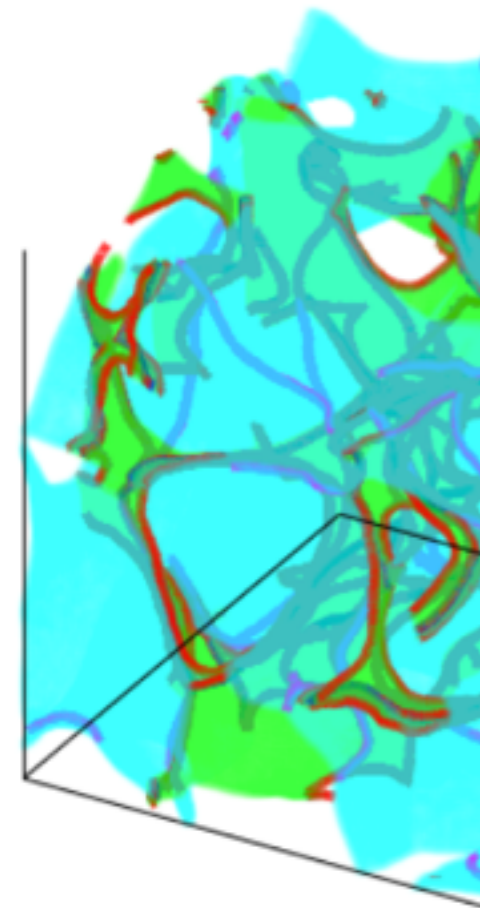


Domain walls remain, stretching between strings, in the case of $N = 2$. They follow the scaling law.

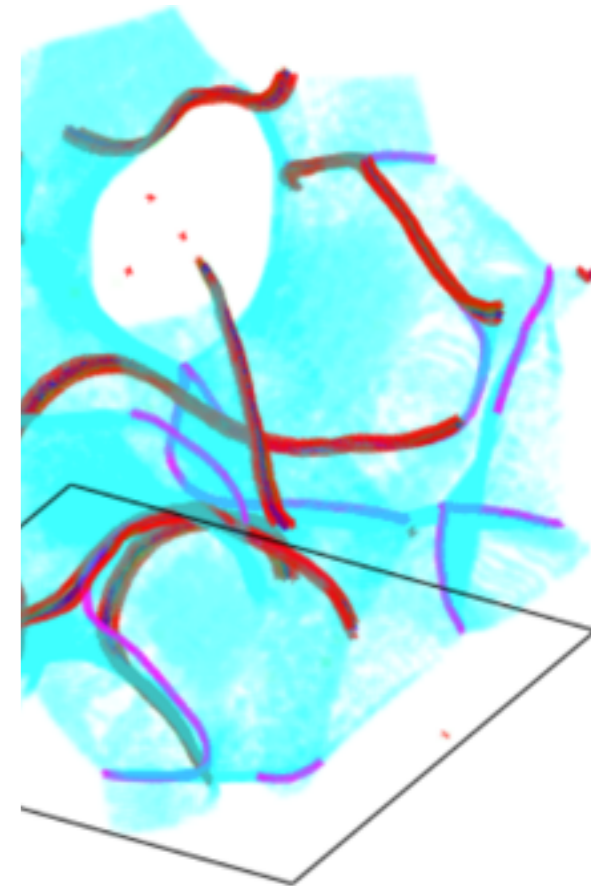
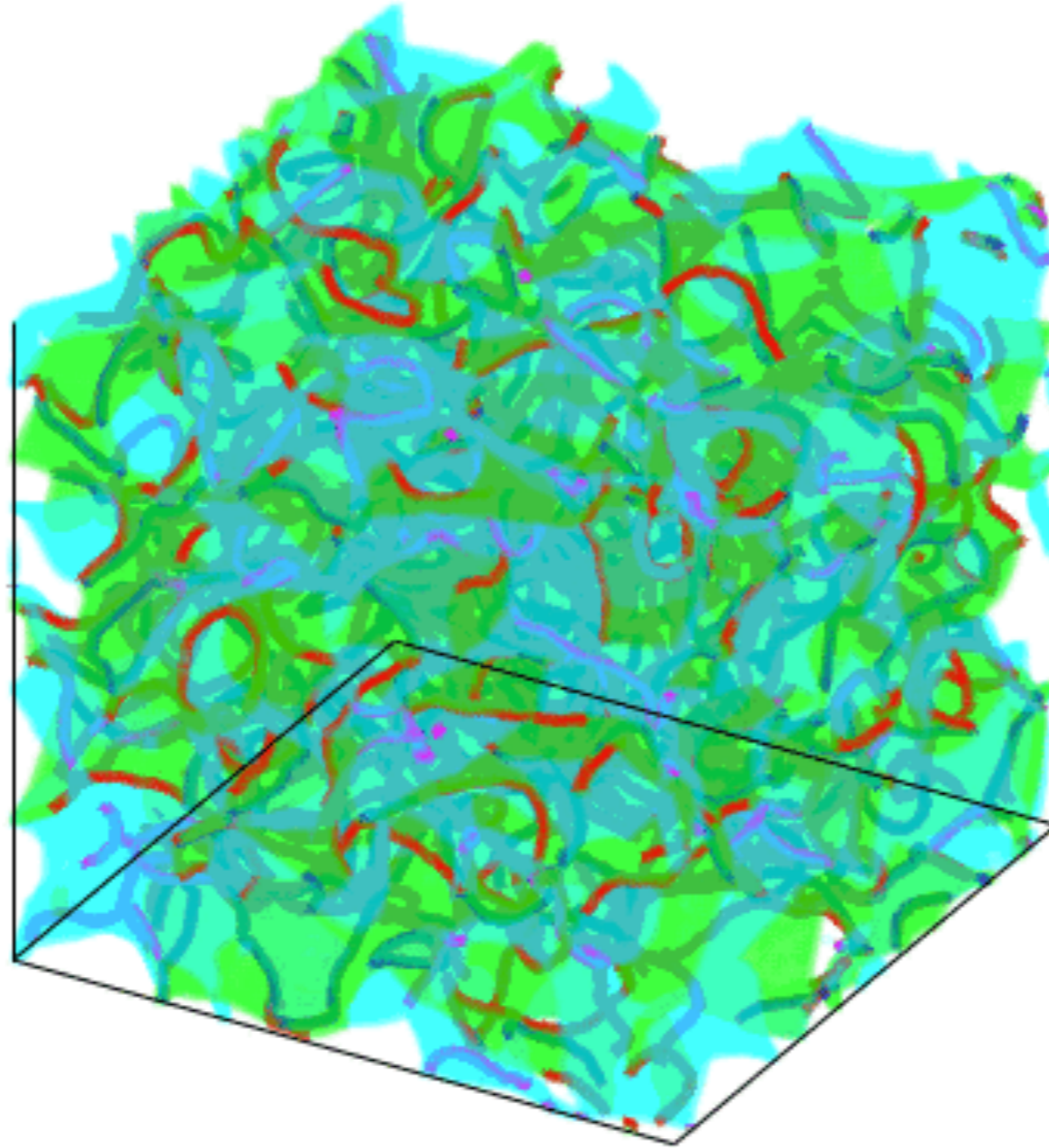
Numerical simulation

Hiroyuki .leond. Kitaiima. Sekiguchi, FT, 1606.05552

$$N = \xi$$



Domain
in the

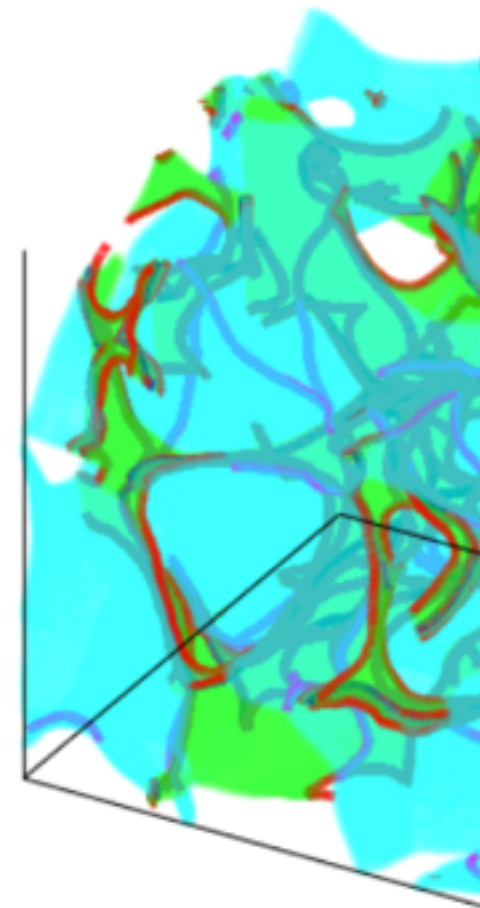


strings,
ng law.

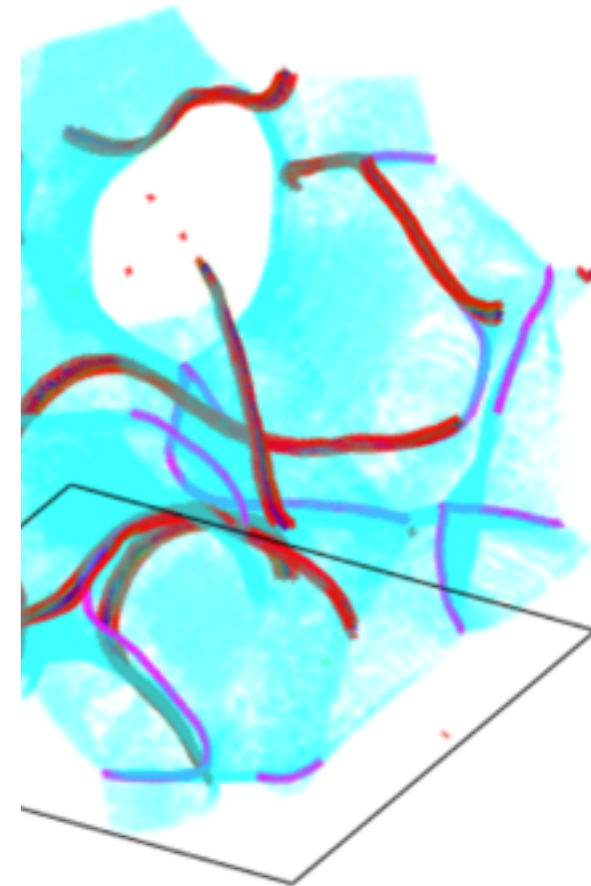
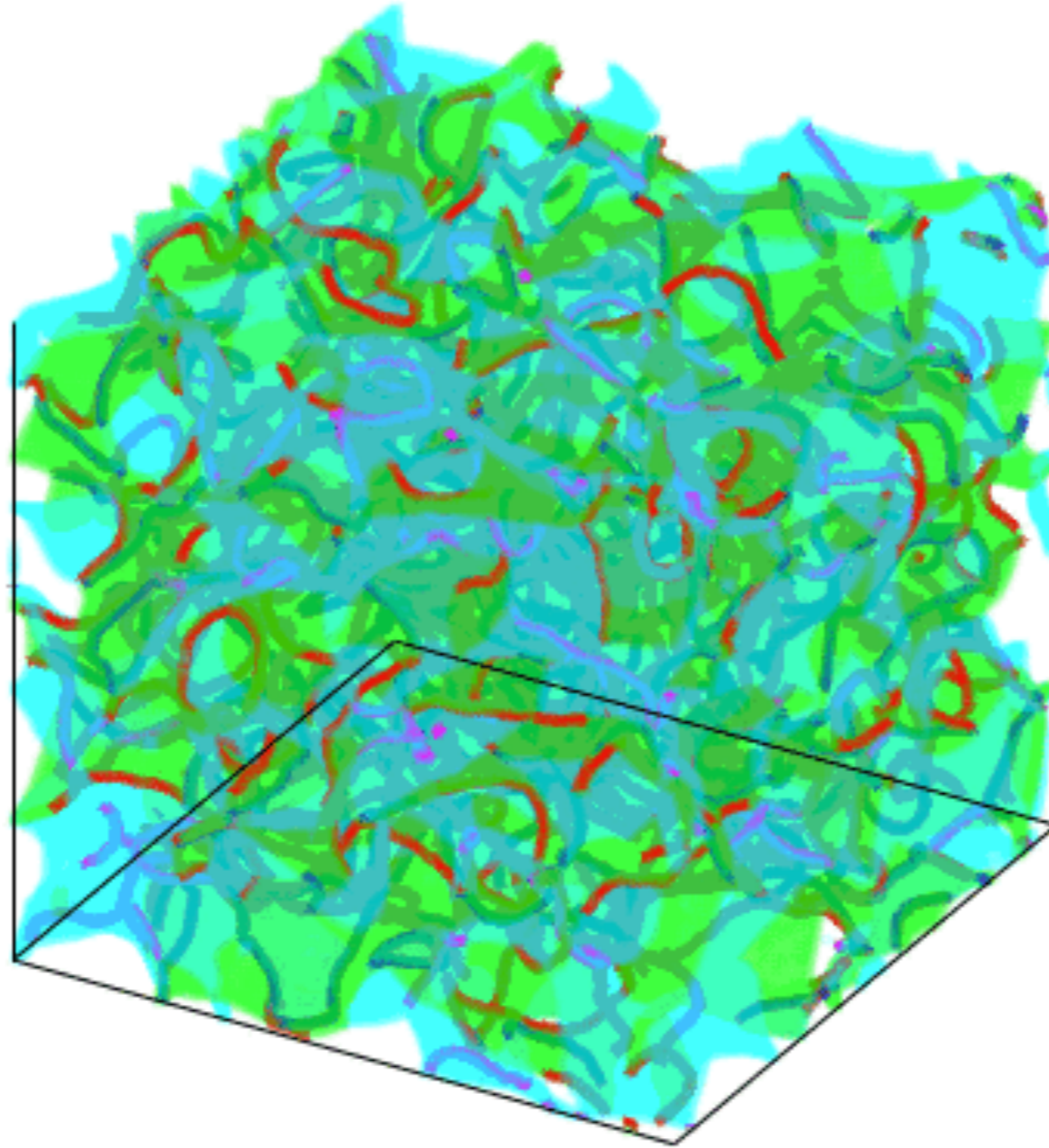
Numerical simulation

Hiroyuki .leond. Kitaiima. Sekiguchi, FT, 1606.05552

$$N = \xi$$



Domain
in the

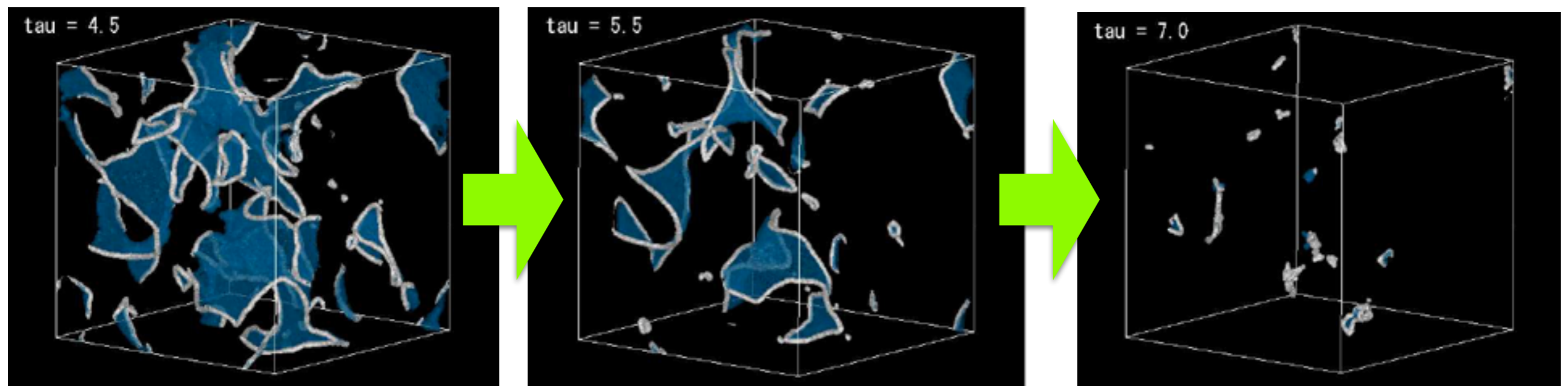


strings,
ng law.

Gravitational waves from domain walls

Higaki, Jeong, Kitajima, Sekiguchi, FT, 1606.05552

The domain walls annihilate at the QCD phase transition, producing a significant amount of gravitational waves.



Hiramatsu, Kawasaki, Saikawa, Sekiguchi,
1202.5851

Gravitational
waves



Gravitational waves from domain walls

Higaki, Jeong, Kitajima, Sekiguchi, FT, 1606.05552

The peak frequency is determined by the Hubble horizon at the QCD phase transition.

$$\nu_{\text{peak},0} \simeq 1.6 \times 10^{-7} \text{ Hz} \left(\frac{g_{*\text{ann}}}{80} \right)^{1/6} \left(\frac{T_{\text{ann}}}{1 \text{ GeV}} \right)$$

Amount of GWs: $E_{GW} \sim G \frac{M^2}{R} \sim G \frac{(\sigma H^{-2})^2}{H^{-1}}$

The energy density of walls: $\rho_{dw} \sim \sigma H$

The tension of walls: $\sigma = 8m_{aH} f^2 \quad m_{aH} \sim \sqrt{\epsilon} f$

Gravitational waves from domain walls

Higaki, Jeong, Kitajima, Sekiguchi, FT, 1606.05552

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GW density parameter:

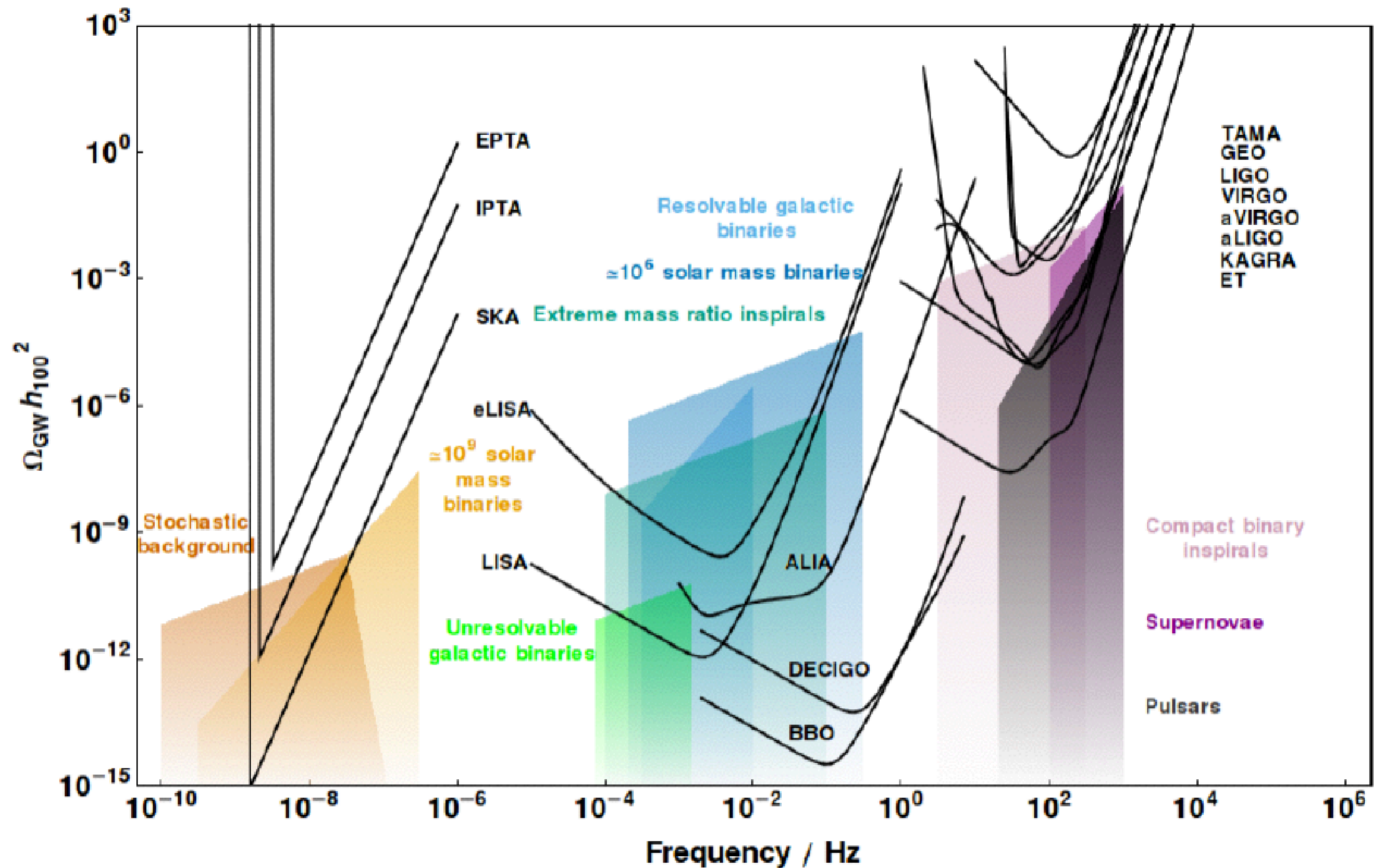
$$\Omega_{GW}(\nu_{\text{peak}})h^2 \simeq 2 \times 10^{-11} \epsilon \left(\frac{g_*}{80} \right)^{-\frac{4}{3}} \left(\frac{T_{\text{ann}}}{1 \text{ GeV}} \right)^{-4} \left(\frac{f}{100 \text{ TeV}} \right)^6$$

with a frequency dependence, $\Omega_{GW}(\nu) \propto \nu^3$, for $\nu < \nu_{\text{peak}}$.

Hiramatsu, Kawasaki, Saikawa, 1309.5001

Gravitational waves from domain walls

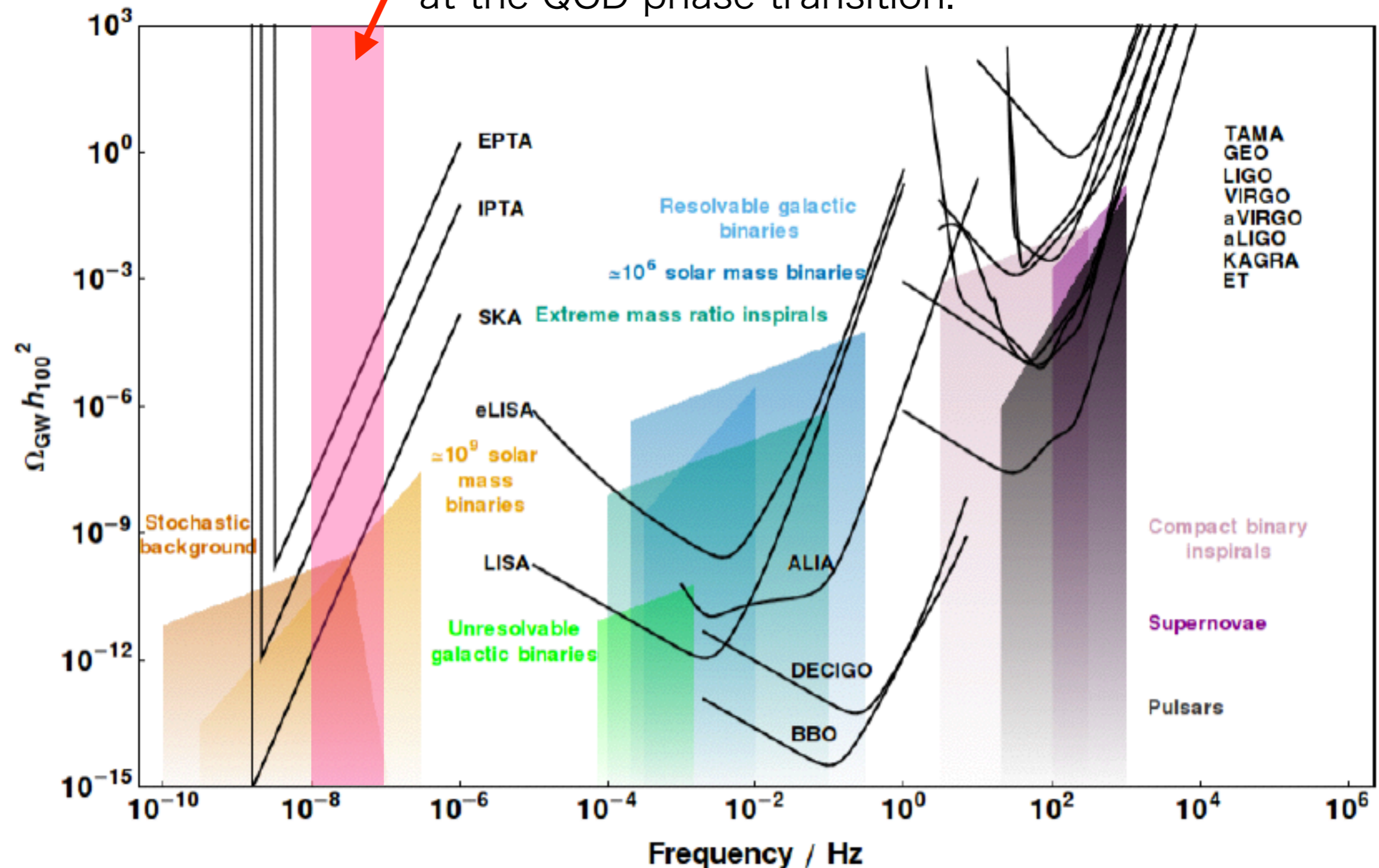
Higaki, Jeong, Kitajima, Sekiguchi, FT, 1606.05552



Gravitational waves from domain walls

Higaki, Jeong, Kitajima, Sekiguchi, FT, 1606.05552

Frequency corresponding to the Hubble radius at the QCD phase transition.



Gravitational waves from domain walls

Higaki, Jeong, Kitajima, Sekiguchi, FT, 1606.05552

GW density parameter:

$$\Omega_{GW}(\nu_{\text{peak}})h^2 \simeq 2 \times 10^{-11} \epsilon \left(\frac{g_*}{80} \right)^{-\frac{4}{3}} \left(\frac{T_{\text{ann}}}{1 \text{ GeV}} \right)^{-4} \left(\frac{f}{100 \text{ TeV}} \right)^6$$

with a frequency dependence, $\Omega_{GW}(\nu) \propto \nu^3$, for $\nu < \nu_{\text{peak}}$.

Hiramatsu, Kawasaki, Saikawa, 1309.5001

Pulsar timing constraint:

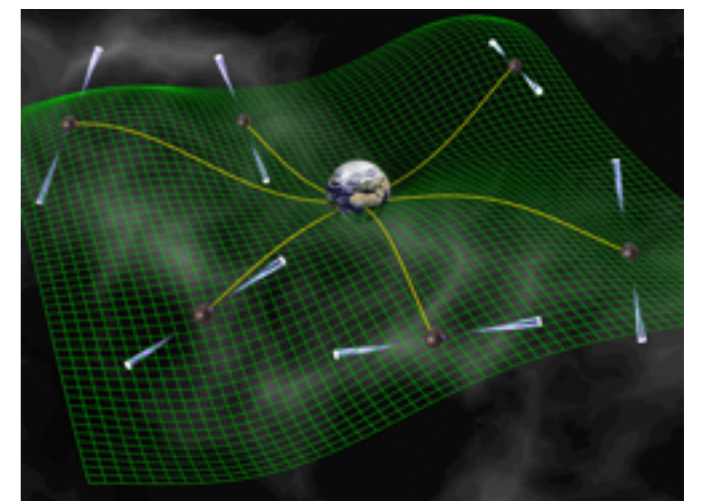
$$\Omega_{GW}h^2 < 2.3 \times 10^{-10} \quad \text{at} \quad \nu_{1yr} \simeq 3 \times 10^{-8} \text{ Hz}$$

P. D. Lasky et al. 1511.05994

Constraint on the PQ breaking scale:

$$f \lesssim 200 \text{ TeV} \times \epsilon^{-1/6}$$

Will be improved by a factor of 2 by future SKA.



credit: D. J. Champion

Summary

The axion isocurvature problem point to either

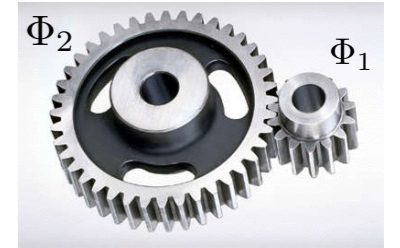
(1) low-scale inflation, $H_{\text{inf}} \lesssim 10^{7-8} \text{ GeV}$

or

(2) various interesting (exotic) possibilities, such as PQ symmetry restoration, axion string-wall system, hidden monopoles, many (s)axions, GWs.

Summary

✓ In **the aligned QCD axion**, the PQ symmetry is likely restored, avoiding the isocurvature bound.



✓ Robust against Planck suppressed PQ symmetry breaking terms.

✓ Domain walls remain until the QCD phase transition, and their annihilation produces nano-Hz GW, which can be searched for by the pulsar timing array.